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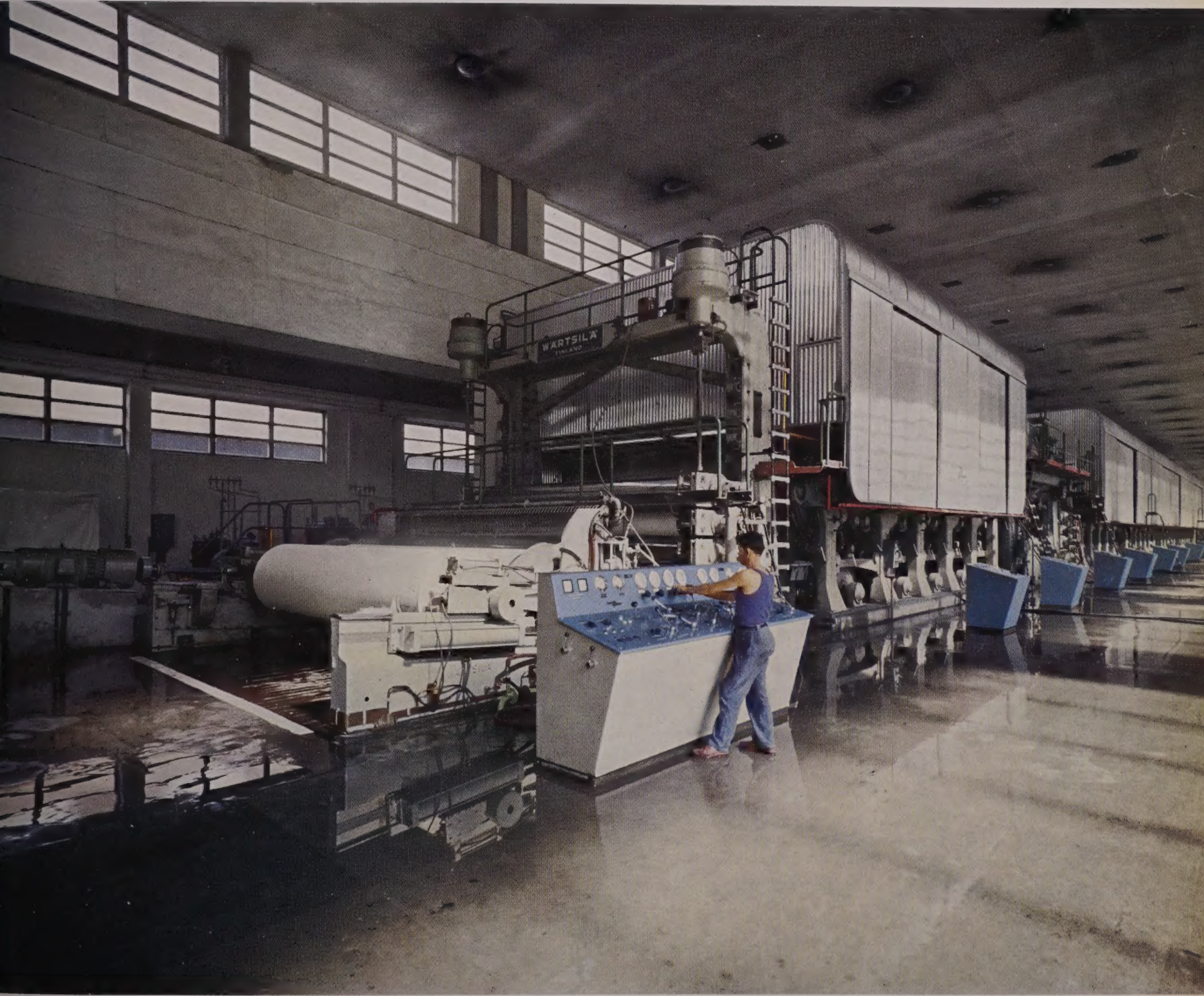
BROWN BOVERI REVIEW

Drives in Paper-Mills and Printing Works



Paper machine with Massey coating section for the manufacture of printing and writing paper, maximum working speed 600 m/min, in the Lancey (Isère) works of Papeteries de France.

Driven by two main d.c. motors, each rated 650 kW, and 21 auxiliary motors with a total rating of about 650 kW.

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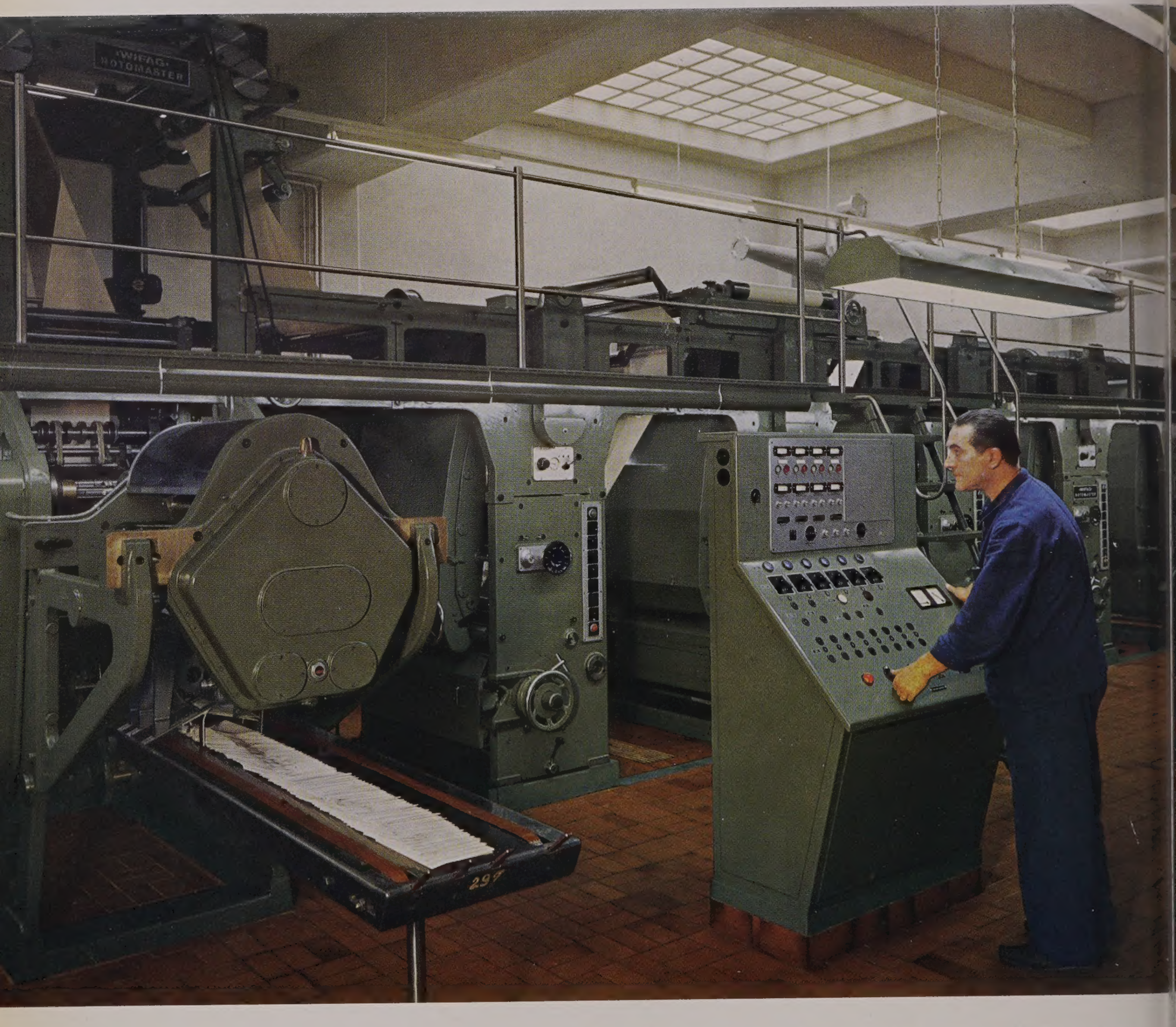

"Rotomaster" rotogravure machine built by Winkler, Fallert & Co., Berne, driven by one 35-h.p. shunt commutator motor without any auxiliary motors, installed in the printing works of Verbandsdruckerei AG., Berne, Switzerland.

THE BROWN BOVERI REVIEW

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CONTENTS:

	Page
E. Oschwald: Drives in Paper Mills and Printing Works	463
H. Kistner: Paper Machines and Their Drives	464
E. Andres: Requirements of Paper-Machine Drives	469
R. Wendt: Controlling the Working Speed of Paper Machines	478
E. Wanner: Control of the Individual Sections of Paper-Machine Drives	489
A. Dudler: Variable-Speed Drives for Winders	501
D. Gabor/E. Fischer: Electric Drives of Super-Calenders	511
H. Präkelt: Reel Drives on Paper Machines	517
P. Wolfensberger: Variable-Speed Drives in Printing Works and Miscellaneous Paper-Processing Plants	523
Publications by Brown Boveri Authors in Other Journals	533

DRIVES IN PAPER MILLS AND PRINTING WORKS

676-83
681.62-83

AT THE START of this century Brown Boveri were already playing an important part in the development and perfection of electrical equipment for the paper industry. The tremendous progress which has been made in the manufacture of paper, from the primitive efforts at the start, over 2000 years ago, to the modern newsprint machine with a top working speed of 900 m/min, was effectively promoted by the services of electrical engineering. The power of the water-wheel is converted into electricity, which can be used anywhere, being distributed to the individual consuming circuits in the factory by a system of increasing ramification. The way the successive sections of the process in paper-making have been combined to obtain a continuous flow is almost a copy-book example of how electrical engineering enables a process to be progressively improved and adapted to increasing demands and working speeds.

In collaboration with paper manufacturers and machine builders, Brown Boveri engineers have performed a great deal of pioneer work in this sphere. In this respect reference may be made to the development of the back-pressure extraction steam turbine used for generating power and process steam, which has been adopted almost universally by the paper industry; also to the fundamental patents and original designs of power control systems for wood grinders, to the design and control of sectional drives for paper machines and centre-driven electro-reelers. Based on the reputation enjoyed as a result, Brown Boveri have always considered it their duty, not to shirk any effort to keep these quality products abreast of engineering progress, adapting them continually to the increased outputs and demands, and adopting new approaches for development of processes, as well as for increasing and improving production. By consistently following the principle of the "all-electric" machine, the mechanical systems of shaft and belt transmissions have given way to sectional drives, in which each section of a process is driven by its own electric motor, and for extremely exacting conditions is equipped with a separate unit-connected generator; to complete the picture such drives are provided with expedient control gear.

The present issue of this journal shows something of the work undertaken in the last few years. The various articles are primarily concerned with the electrical equipment of paper machines, but also deal with finishing and processing machines and their controls. Referring to completed installations they illustrate the present state of progress along the road towards automation of the production. In some cases quite new approaches have been adopted, differing radically from those formerly favoured. This is underlined by the fact that, although satisfied with the standard attained, the Company clearly realizes that evolution never remains at a standstill and at all times welcomes the improvement of existing principles and the introduction of new ideas and elements.

(KME)

E. Oschwald

PAPER MACHINES AND THEIR DRIVES

676.2.052–83

This article describes the basic design and the principles of paper machines, illustrated by a historical review of their development.

The Paper Machine

THE paper machine is a complicated, extensive set of machinery, normally comprising a constant part and a variable part. The constant part includes the stock tanks, or storage tanks, in which the stock produced in the stock preparation plant is collected; also the stock pump, the screens and rifflers, the beaters and digesters, the filtrate pump and vacuum pump.

It is only in the variable part, i.e. the paper machine proper, that the stock is processed to form paper, as we know it. At the wet end (the wire and the presses) the sheet is produced from the stock by the mechanical removal of water. At the dry end the rest of the superfluous water evaporates. Finally the paper is wound into a reel on the reeler at the end of the paper machine. Fig. 1 shows a typical sectional diagram through a modern newsprint or Foudrinier machine.

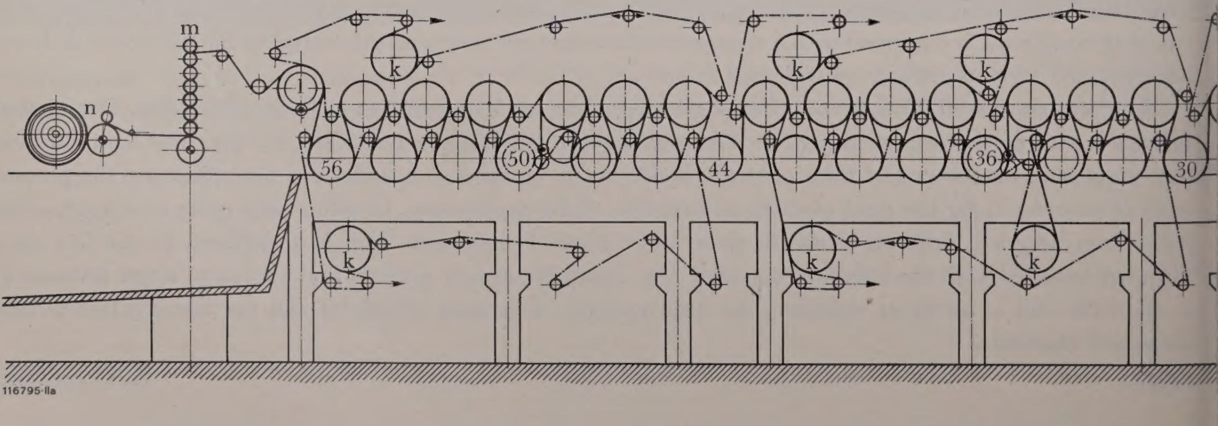
The Wet End

Depending on the design of the particular machine and the purpose it serves, the stock is picked up first by a "wire"—a moving endless belt of wire gauze—or by a cylinder mould, in many cases several cylinder moulds. On some machines, for instance board machines, both systems are employed.

On the paper machine illustrated in Fig. 1, which is a high-speed newsprint machine with a wire, the stock flows from the headbox *a* on to the breast roll at the beginning of the wire *b*. On the wire the water is removed from the stock by suction in addition to simple dripping, and this produces

Fig. 1. – Sectional view of a paper machine built in 1957 with a top speed of 750 m/min

Wire width 5700 mm, 19 drive sections, total rating of all motors 4780 h.p., of which the stock pump drive accounts for 505 h.p. The second and third of the four identical driers have been omitted for space reasons.



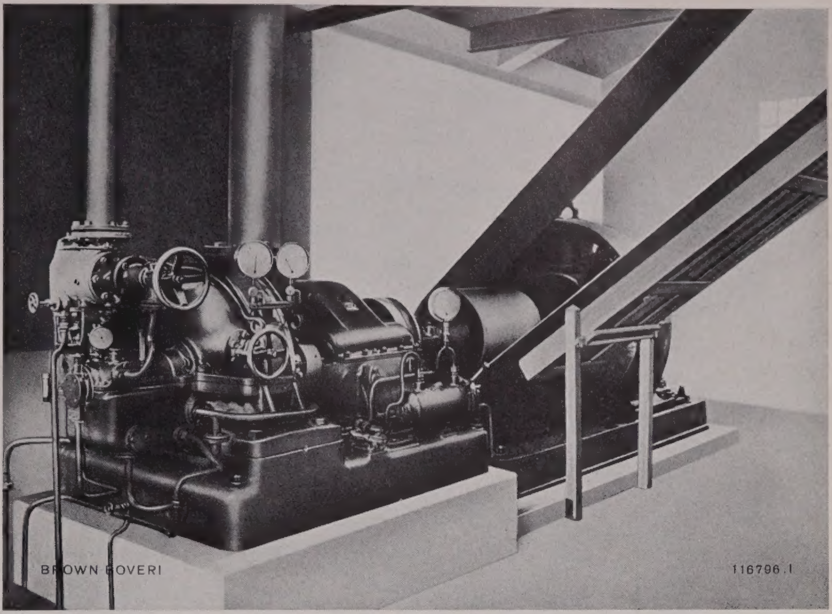


Fig. 2. – Back-pressure steam turbine rated 220 h.p. driving a paper machine (supplied in 1925)

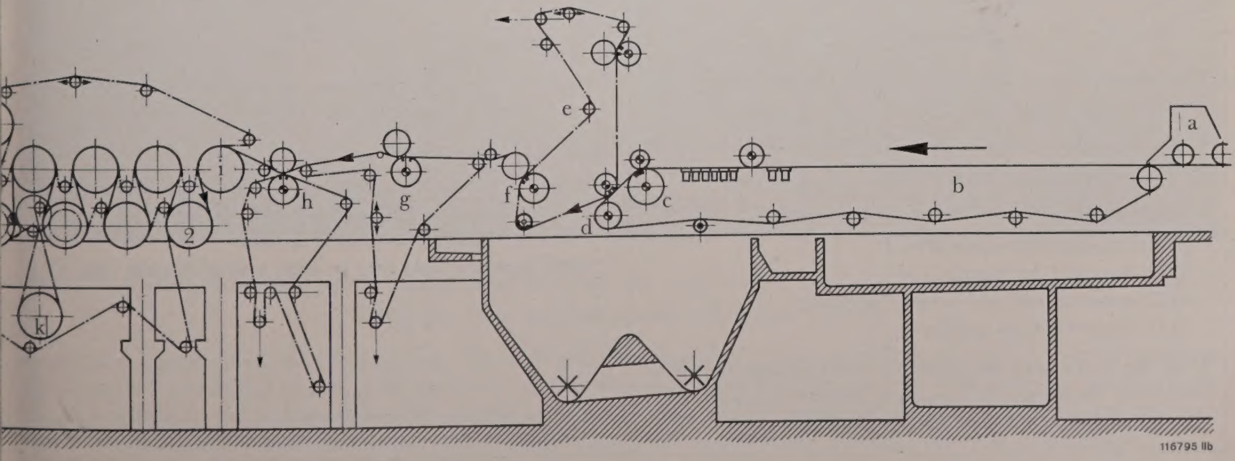
The relatively high speed of the turbine is adapted to that of the machine by a reduction gear and can be varied to suit the desired working speed. The drive power is transferred by a belt drive to the longitudinal transmission of the machine. Coupled to the turbine is a generator which feeds the auxiliaries. If the turbine is not to run under uneconomical conditions, the working speed of the paper machine may only vary in close limits. In the case illustrated the working speed range is 1:1·5.

the sheet. At the end of the wire the sheet runs over the couch roll *c*, while the wire belt passes over the forward drive or diverter roll *d* and a series of guide and tensioning rollers, back to the breast roll. The diverter roll and vacuum pick-up are only required on very high-speed paper machines.

In the machine illustrated the felt of the pick-up section *e* makes contact with the paper sheet between the couch roll and the diverter roll. The sheet adheres to the underside of the felt and is carried by it to the first transfer press *f*. While passing through this press the sheet is picked off the felt. While the latter continues over the guide rolls and the wringer in the upper part of the system, the paper sheet, which is now strong enough to support its own weight for a short distance, is transferred to the felt of the second press *g*. This felt conveys the still wet sheet to a point just before the third press *h*.

The Dry End

On leaving the third press the paper sheet enters the dry end of the machine, the cylinders of which



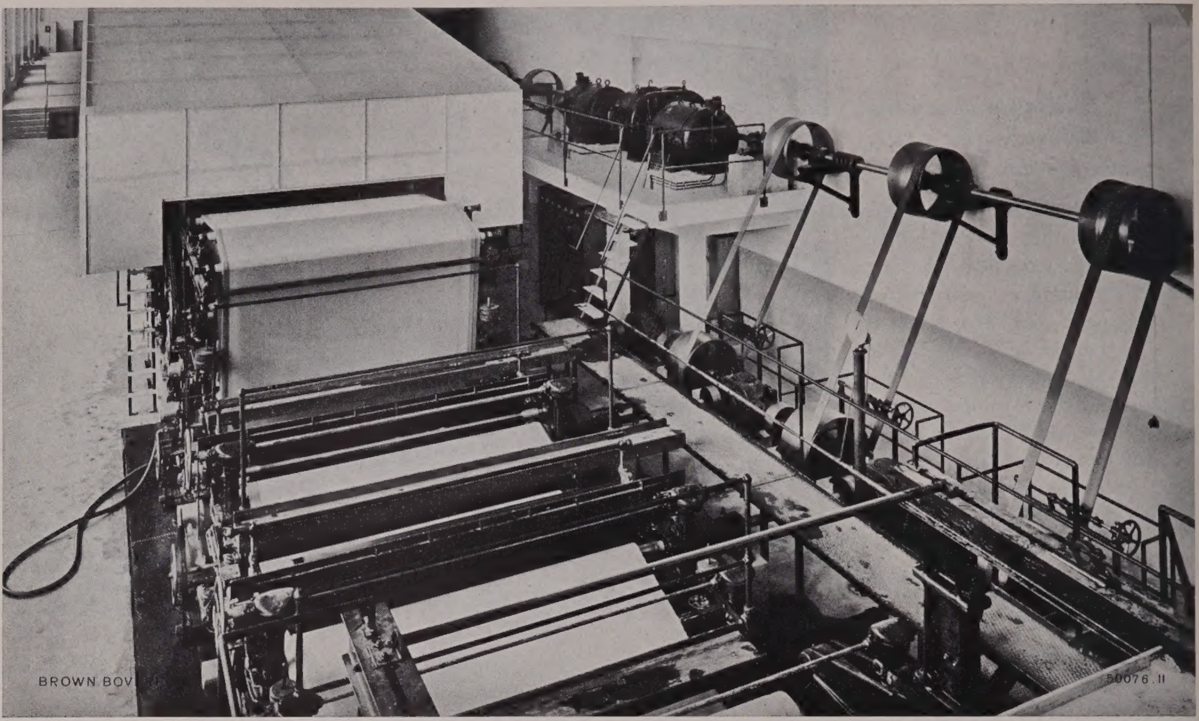


Fig. 3. – Two three-phase shunt commutator motors, each rated 92 kW at 900 rev/min driving the longitudinal transmission of a board machine through three-stage gearing (installed in 1940)

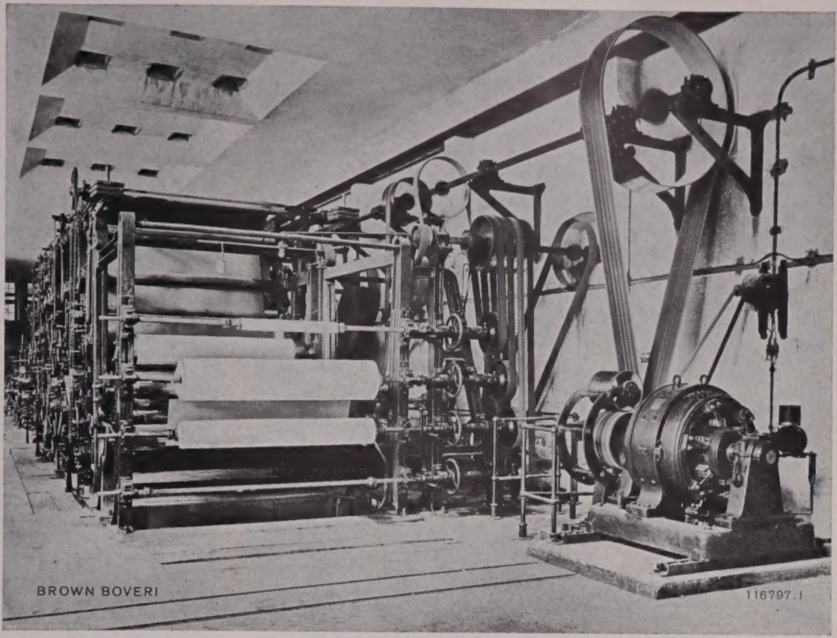
This board machine has a wire and a cylinder mould, the width of which is about 2·8 m. The working speed can be varied between 5 and 120 m/min. In this extraordinarily wide range the drive operates very economically because when only a small amount of power is required, i.e at the lower end of the speed range, only one of the motors is switched on. At the upper end of the range, with both motors in action, the load is evenly distributed between them by an automatic system. Depending on how they are to operate, the two motors can be coupled up with the transmission shaft through the gear pinion by means of a clutch. The secondary shaft of the gear is coupled at both ends with the transmission shaft. Some of the conical pulleys can be seen, one on the transmission shaft, the other on the machine. Also visible against the side of the machine are the section gears, which in this case are designed as crown gears.

Alternative methods of driving paper machines

Longitudinal transmissions	Sectional drives (no transmission)
The transmission is driven by a single steam engine with variable speed (Fig. 2) The transmission is driven by a steam engine with constant speed, through a speed-change gear The transmission is driven by an electric motor: Shunt commutator motor (Fig. 3) Ward-Leonard d.c. motor D.C. motor in buck and boost (Fig. 4) D.C. motor fed from rectifier In all the above cases the power is transferred from the transmission to the sections of the paper machine by belts on to tapered pulleys or by speed-change gearing	Sections of the paper machine are driven by three-phase shunt commutator motors (Fig. 5). Sections are driven by d.c. motors: Ward-Leonard main generator (Fig. 6) Main generator in buck and boost (Fig. 7) Main generator replaced by a rectifier Main generator split into separate unit generators (Fig. 8)

Fig. 4. – This 60-h.p. d.c. motor built in 1927 operates in buck and boost, and has a speed range of 72–720 rev/min

To save space, the longitudinal transmission in this case was mounted on brackets along the wall. A few of the large number of drive belts can be seen, transferring the power from the transmission to the sections of the paper machine. A quick-acting control system, actuacted by the small tacho-generator on the wall above the motor in the foreground, maintains constant speed.



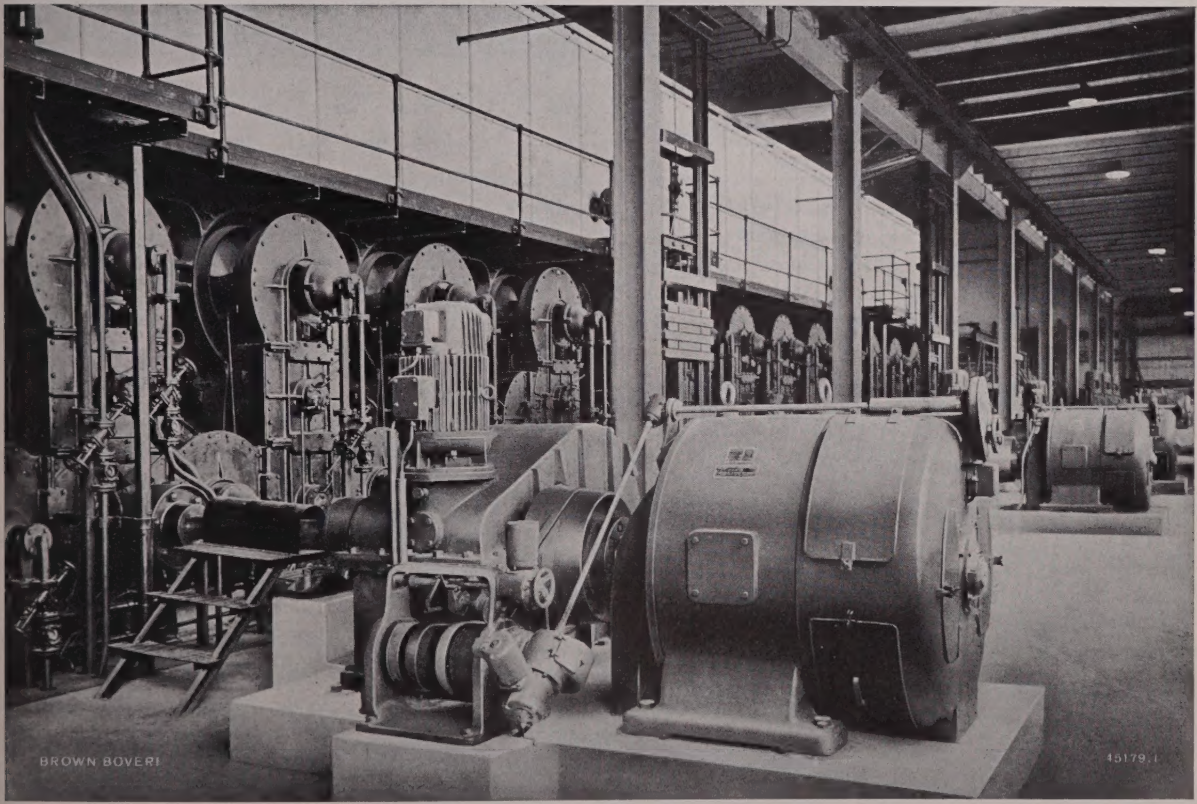


Fig. 5. – This paper machine, with a wire width of 3950 mm and a top working speed of 500 m/min is driven by a number of three-phase shunt commutator motors (installed in 1938)

In the foreground are the drives of the dry end. The working speed is controlled (remote) by shifting the brushes. The draw between the sections is kept constant by draw regulators, for which the frequency of the tacho-generator on each section is compared with a master frequency. The conical pulley at the coupling between the motor and the gearing affords infinite adjustment of the draw. For the auxiliary speed each section is also equipped with a three-phase motor (mounted vertically on the gearing).

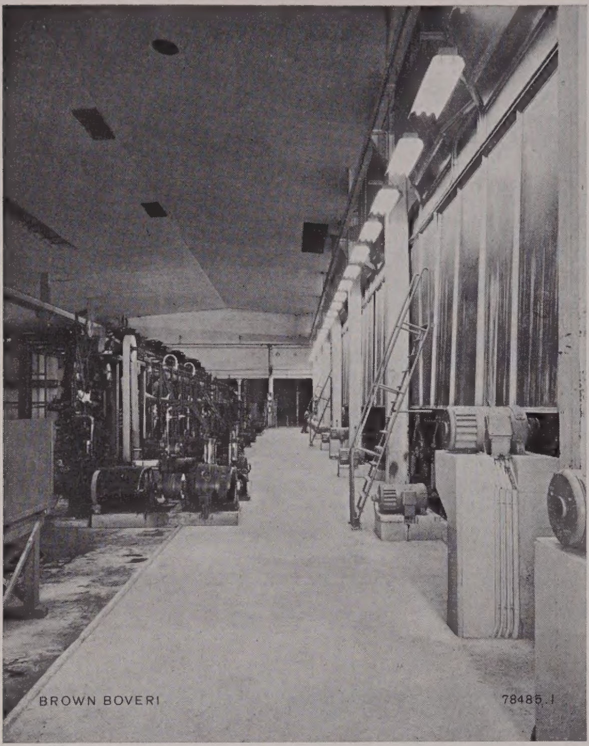


Fig. 6. – Two Ward-Leonard sectional drives for paper machines. Left, installed in 1927; right, installed in 1952

Whereas on the older machine the draw is still adjusted by means of conical pulleys and belts, visible at the couplings between the motors and gearing, all the control gear for the new machine is accommodated in a separate room. The paper machines, in particular the new machine, are easily accessible on the drive side.

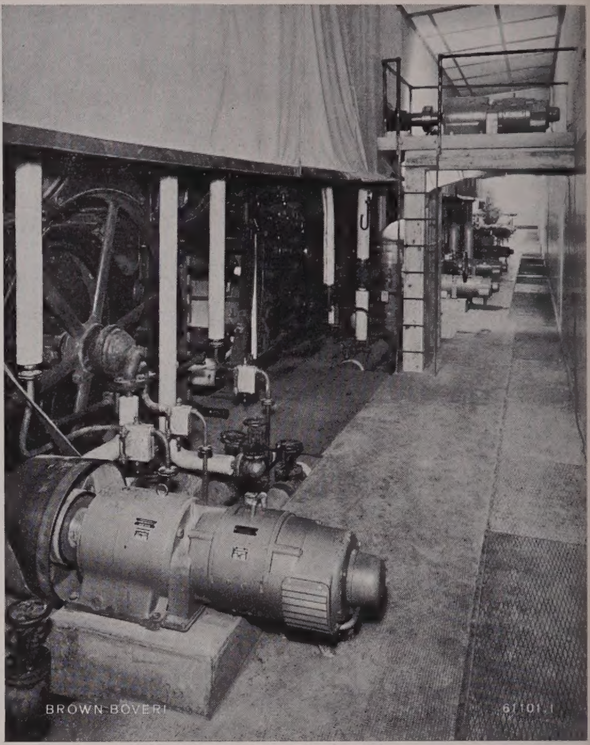


Fig. 7. – Sectional drive of a board machine connected in buck and boost (installed in 1942)

In the foreground is the joint drive for the after-drier and cooling cylinder. Top right can be seen the drive for the large Yankee cylinder, with the other drives of the dry end further to the rear. Right at the back is the wet end. Note the easy access to the drive side of the machine.

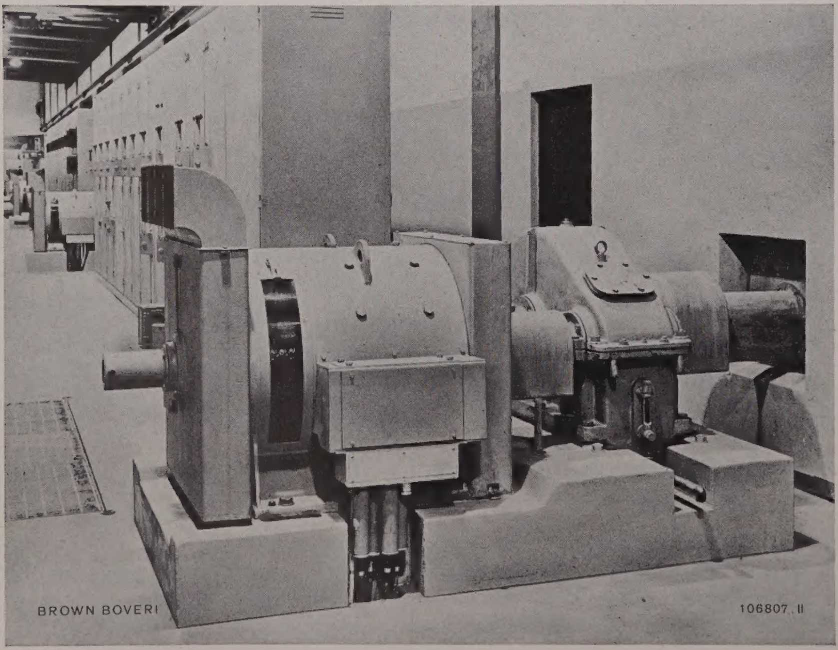


Fig. 8. – Part of the room housing the drives of a modern newsprint machine (installed 1957/8)

The motor room is separated from the paper machine by a wall.

In the foreground is the motor and gearing for one of the four driers, each with a drive power of 380 h.p. Mounted along the wall are the cabinets containing the switchgear and all the protective gear for the motors and generators. Beyond the cabinets is another drier drive, followed by the cabinets containing the control gear. Right at the back some of the motors of the wet end are just recognizable.

are heated with steam on the inside. The large number of cylinders at the dry end (in the case illustrated there are 56 paper driers *i*, 14 felt driers *k* and one cooling cylinder *l*) cause the residual, superfluous moisture in the paper to evaporate. On account of the large number of cylinders, the dry end is subdivided into four parts, each of which is driven separately. After leaving the dry end the paper is cooled on the cooling cylinder *l*, given a smooth surface by the calender *m* and finally wound on the reel *n*.

The Drive

The Table at the bottom of page 466 gives a brief summary of the different possible drive systems, while Fig. 2 to 8 depict a number of installations equipped by Brown Boveri between 1926 and 1958.

(KME) H. Kistner

REQUIREMENTS OF PAPER-MACHINE DRIVES

676.2.052–83

The requirements regarding inching, auxiliary speed, starting and braking, and the adjustment of speed and draw, imposed on the drives of a paper machine, are briefly explained in the present article. Then the alternative systems with longitudinal transmission, single-generator sectional and multi-generator sectional drives are compared. Finally details are given regarding the maintenance of the draw and working speed on paper machines.

The drive of a paper machine has to comply with numerous requirements. On the one hand it is important for the entire machine, and also the individual sections, to be easily controlled. On the other hand strict conditions are stipulated regarding maintenance, to a high degree of accuracy, of the relative speeds—known as the "draw"—between the individual sections, as well as on the overall paper speed.

The most exacting conditions are imposed by a high-speed newsprint machine with a very wide wire. The remarks which follow will therefore be confined mainly to a machine of this kind. They are, however, equally applicable to smaller and slower machines, but having regard to the prevailing conditions, will have to be applied in accordance with their importance and magnitude.

Controllability of a Paper Machine

For drawing in the felts, cleaning the machine, running-in the felts, heating up the dry end, adjustment of the relative speeds (draw) and the paper speed, as well as for starting and stopping the individual sections in the event of a stoppage, the machine must be equipped with a very flexible control system. This is an important factor in the economic operation of the paper machine. Consequently the drive must be capable of performing the actions of inching, crawling, starting and braking, and afford facilities for adjustment of the paper speed and draw. Let us now examine these requirements in some detail.

Inching: When the wire is being cleaned it has to be moved forward a few inches at a time, so that it can be cleaned and inspected properly. Also when pulling in the felts and lead ropes this operation is important. The motor concerned only has to move forward as long as the particular button is pressed. Even if this lasts some time, the speed must not exceed 10–25 m/min.

Crawling: Every section should be able to run at the crawling or auxiliary speed of 10–25 m/min. This is necessary for "running-in" the felts and the wire. It is advantageous if several sections can be run simultaneously at this speed. Operation is further simplified if this speed can be set individually between 10 and 100 m/min on each section. The other sections should be able to run at normal speed at the same time.

Starting and braking: Every section must be able to accelerate from standstill to full working speed. During this acceleration the maximum admissible mechanical torque, given by the type of gear chosen, must not be exceeded. At the end of the acceleration process the working speed must be assumed smoothly, without over-running. It may happen that paper is running through the machine while starting or braking is taking place in the last two sections, i.e. the calender and the reeler. In such a case the effects of the starting or braking current must not be sufficient to cause such a change in speed that the paper tears. It is also possible for the acceleration to be limited by the machine itself. For instance, care must be taken to ensure that there is no slip between the wire and the driving roll.

On account of the heavy masses of the dry end, especially on high-speed machines, switching off the section drive without simultaneous braking would result in far too long a run-out. Braking is therefore essential on high-speed machines. As regards retardation, the conditions are the same as for acceleration.

Speed setting: Depending on the particular manufacturing programme, the paper machine may have a wide or a limited speed range. In the case of machines producing newsprint it is quite small, i.e. 1:2 to 1:3, whereas for multi-purpose machines it can be up to 1 : 10. It should be possible for the working speed to be continuously adjustable. Frequently a sensitivity of 0·1% is stipulated. The question of maintaining the set speed will be dealt with later.

Draw setting: Between individual sections the paper sheet hangs freely without any support. Depending on the amount of water it contains and the quality of the stock, a definite tension must be set and regulated. This necessitates a definite difference between the speeds of successive sections. The adjustment of the corresponding speed differences is referred to by paper-makers as the "draw". For a particular kind of paper the speed difference between the wire and the reeler is always the same. It is possible, though, for different conditions to be laid down regarding the removal of the water, in which case the speeds of the sections concerned must be varied without affecting the speed of the preceding or the succeeding section. Furthermore, to prevent the draw settings from being adjusted to an end position, one section must be chosen to be the "fixed point". It has proved convenient to make this the first drier section.

The range of draw adjustment should be about ± 5–7%, referred to the normal working speed. The conditions regarding the sensitivity of the draw adjustment will be dealt with in a later chapter. Here it is merely mentioned that the set or indicated draw must be exactly equal to the actual tension. Moreover the draw setting should permit adjustment to within 0·1%.

Controllability of the Various Kinds of Drives

Longitudinal Transmission

For drives with a longitudinal transmission shaft inching is performed by actuating a clutch between the drive and the section of the machine. On large machines auxiliary or helper motors with clutches are provided, permitting both inching and crawling (Fig. 1). In addition, the helper drive can also be employed for braking the section, the motor being connected at standstill with the machine through a torque-controlled coupling. The braking energy is then converted into heat, thereby imposing very severe conditions on the coupling, usually resulting in appreciable wear.

For starting, a definite torque can be set on the coupling. For most systems the draw setting should suffice under the majority of conditions. The working speed setting acts upon an electrical control system and can easily be adapted to the conditions by correct dimensioning.

Single-Generator Sectional Drive

The simplest circuit is that with a starting resistor, as shown in Fig. 2. When the command is given for inching, contactor 9 is closed, the armature of the section motor experiencing the voltage of generator 2 through resistor 6. Similarly the motor can be brought up to the crawling speed. If the ratings of the section motors are very different, it may be necessary to incorporate two or three starting systems. The sections are likewise started up through the resistor 6, which is gradually short-circuited by a programme switch or current relay. At the end of the starting process the voltage of generator 2 is applied direct to the motor by means of contactor 8. The starting system is then ready to start up the next motor. The number of steps and the time between steps is made such that the maximum admissible torque is never exceeded, even at top working speed. This circuit has given very good results in numerous small and medium machines.

The control of the draw will be referred to later. Setting by transmission with a selsyn is very practical and accurate. Changes in the draw of less than 0·01% can be set with ease. A Brown Boveri sectional drive of this kind also fulfils the requirements regarding the ability to set the working speed.

The drive can be improved by introducing the auxiliary generator, as shown in Fig. 3. In this way a more definite auxiliary speed is attained, completely independent of the load. Moreover, this auxiliary generator can be designed to supply several sections, enabling them all to run at the crawling speed at the same time. With the auxiliary generator it is also possible, during overhauls, for individual machines to be run without the main generator having to be started.

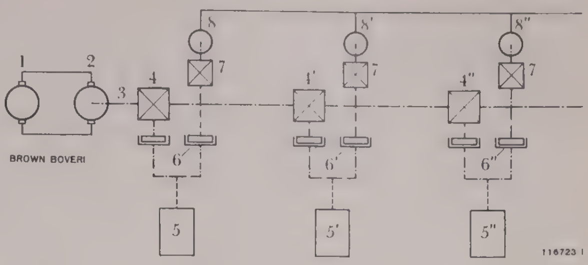


Fig. 1. – Longitudinal shaft transmission with variable-ratio gearing and auxiliary motor for crawling and braking

1 = Generator
2 = Motor
3 = Transmission shaft
4 = Variable-ratio gear
5 = Section of paper machine
6 = Pneumatically operated clutch
7 = Reduction gear
8 = Auxiliary motor for crawling and inching

On large machines it is convenient to replace the starting resistor by a starting generator, equipped with a system of limiting the current, so that the sections can be accelerated steplessly up to the set working speed. On reaching this speed they are automatically switched over to the main generator. There are many variants of this arrangement, each of which affords a favourable solution in one case or another. For instance, after accelerating the last section motor, the starting generator can be switched in parallel with the main generator and allowed to take over a share of the load. With this circuit it is also possible, for example, to brake the dry end when shutting the machine down. Finally, starting surges are prevented from affecting the busbars, which may be considered a further advantage.

With a starting generator and auxiliary converter we come a stage nearer to the optimum controllability of a paper-machine drive. Another circuit

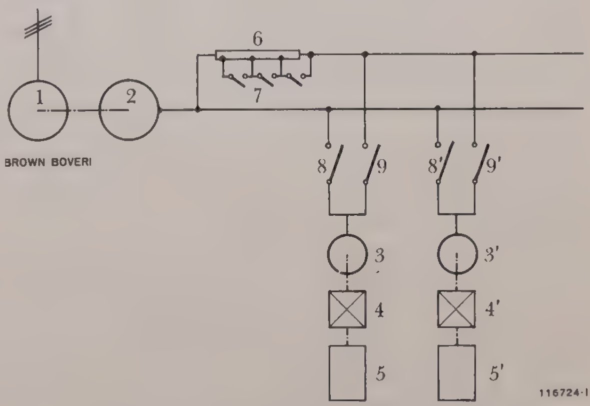


Fig. 2. – Sectional drive with starting resistor

1 = Converter motor
2 = Converter generator
3, 3'... = Section drive motors
4, 4'... = Gears
5, 5'... = Sections of paper machine
6 = Starting resistor
7 = Starting contactor
8, 8'... = Operating contactors
9, 9'... = Contactors for starting, inching and crawling

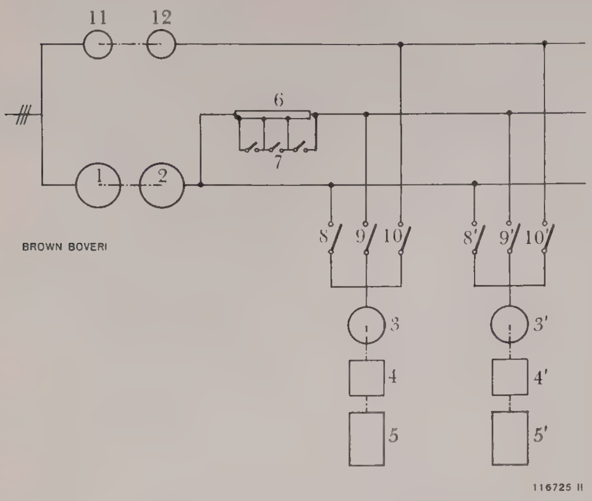


Fig. 3. – Sectional drive with starting resistor and auxiliary generator for crawling and inching

1–8 as in Fig. 2

9, 9′. . . = Starting contactors
10, 10′. . . = Contactors for crawling and inching
11 = Motor driving auxiliary generator
12 = Auxiliary generator

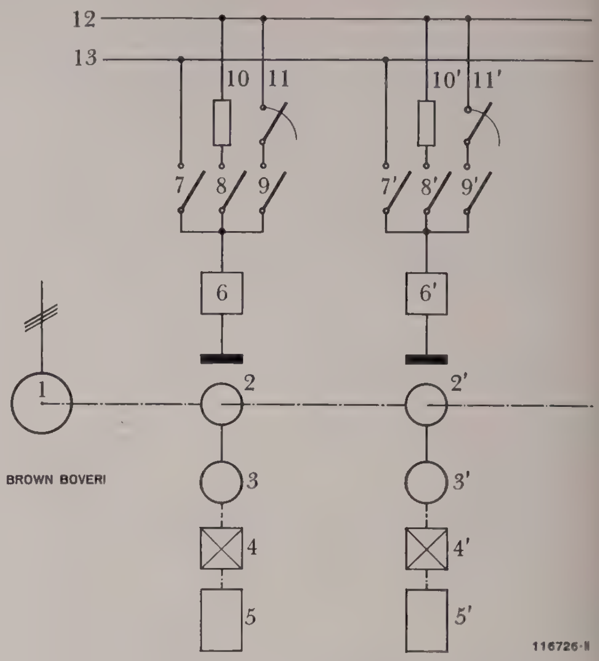


Fig. 4. – Multi-generator sectional drive

1 = Motor
2, 2′. . . = Generators
3, 3′. . . = Motors
4, 4′. . . = Gears
5, 5′. . . = Sections of paper machine
6, 6′. . . = Controller and exciter cascade
7, 7′. . . = Contactor for normal running
8, 8′. . . = Contactor for inching
9, 9′. . . = Contactor for crawling
10, 10′. . . = Rheostats for inching
11, 11′. . . = Rheostats for crawling
12 = Constant voltage
13 = Master voltage

combination uses boosters in series with the armature circuit of the section motor. This method is particularly interesting on account of the excellent dynamic response. Even when a mechanically tied section of a paper machine is driven by several motors, for instance the wire and the take-off section with the first press on Yankee machines, the correction command from the regulator must be given simultaneously and in the same magnitude to all sections, which is best performed by a booster. The latter can then also be utilized for inching and crawling. For switching on the sections the previously described systems with starting resistor or starting generator may be used.

Multi-Generator Sectional Drives

Optimum conditions combined with simple circuitry are, however, obtained with multi-generator sectional drives. In this case every section has its own generator, which performs the duties of auxiliary, starting and main generator. The control unit 6 (Fig. 4) employed for regulating the set tension acts on the generator and adjusts it to the desired operating condition, without a contactor having to be operated in the main circuit. All commands in the control circuit are executed at a very low power level. Moreover, the crawling speed, which is variable over a wide range, is regulated and thus does not depend on the load. The transition from one operating condition to another can easily be adapted to the mechanical conditions by means of the built-in system of current limitation. Thus the sections can be steplessly accelerated or retarded in the shortest possible time. Each section can be manoeuvred independently, regardless of the state of the others. It is thus possible to clean the wire and draw in a felt at the same time, while heating up the dry end. Manoeuvring one section has no effect whatsoever on the rest of the machine.

Summarizing, the following advantages are to be gained as regards the controllability of multi-generator sectional drives:

Starting at optimum acceleration, free from surges;

Minimum braking time, adapted to mechanical conditions;

Ability to manoeuvre all sections simultaneously;

Simple circuitry, no control switch in the main circuit;

Selective interruption in the event of over-current;

The main switch need only be designed for the short-circuit rating of the section generator;

Manoeuvring one section has no effect on the others;

Regulated and individually adjustable auxiliary speed.

That these advantages play an important part in service has been proved by experience gained in installations supplied. As will be explained later, multi-generator systems have gained ground since the introduction of high-speed control systems. The consequent extra outlay for the greater number of machines is worth while, especially for large paper machines.

A study of the different Brown Boveri drives for paper machines shows that a number of well-tried circuits are available, which comply with the requirements of any paper machine as regards controllability. When deciding whether to select the one or the other drive system, it is advisable to study the above requirements as well as the economical aspect and the technical side of the control problem.

The Regulation of the Draw and Working Speed on Paper Machines

Relative Speed or Draw

Tears in the paper sheet during production may be due to a number of reasons. They may, on the one hand, be due to the composition of the stock, the proportion of dry matter, the presence of impurities in the stock, and breakages at the edges of the paper sheet. But deviation from the speed relationship between successive sections can also lead to tears. Whereas certain faults, such as edge breakage and impurities only occur sporadically, the content of dry matter, composition of the stock, flaking and relative speed will crop up over a fairly wide band. If the effects of such phenomena at a certain moment are in the same sense, and at the extreme limits of the scatter band, the risk of the paper tearing is very great. But the paper may only be weakened at the point in question, and there is then a risk of the paper tearing in a subsequent section, due to a change in the tension. Tears always occur at the points where the stress is greatest, and where the paper is unsupported, i.e. at the transfer points. At these points the manner in which the paper is directed, and the flow of air are very important. But the combined effect of all these factors is very difficult to assess. It may merely be stated that production can be increased by narrowing the scatter bands.

In the case of wires without a pick-up roll (Fig. 5) the admissible maximum speed is determined by the ratio of the wet strength to the wet weight. By removing more moisture the dry content rises, and with it the strength, while the weight decreases, and at the same time the elongation on breakage. Now the amount of water which may be removed is restricted by economical and technological considerations. If the speed of a given machine is

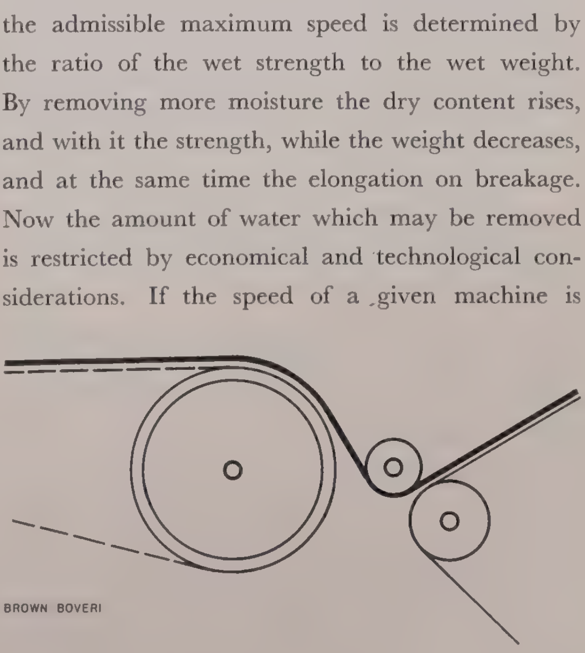


Fig. 5. – Open transfer of paper from the couch roll to the first press

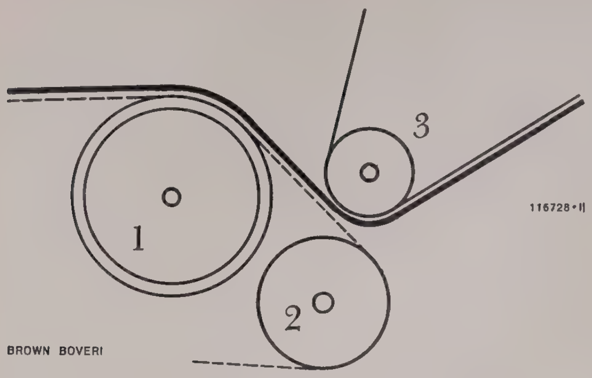


Fig. 6. – Transfer of the paper with pick-up

1 = Couch roll
2 = Forward drive roll
3 = Pick-up roll

increased without the removal of moisture being improved by the same proportion, the dry content automatically decreases. Extension continues to increase until it reaches the breaking point. To maintain safe production, however, the stretch may only be permitted to grow to a point at which there is a safety margin corresponding to the sum of the scatter bands. Hence production can only be increased by reducing the width of the scatter bands. However, for instance with newsprint, which in the wet state on the wire contains 79–82% of water and has a tensile strength of about 4 kg/m, as the moisture is removed the strength increases until, with a moisture content of 6–10%, the strength is 150–200 kg/m and the paper can support itself for a length of 3000–4000 m, as on the reeler. Of course, the wetter the paper, the more easily it can stretch. Between the wire and the first press it is usual to allow a stretch of 3–7%.

If for a particular machine and type of paper the scatter band were known for the admissible stretch, it would be possible to exactly judge the effect of the relative speed band. The main causes of changes in speed are mains fluctuations (voltage and frequency) and changes in the loading. The manner in which mains fluctuations are prevented from affecting the drive are dealt with later. If we assume for the time being that they can be kept to a very small figure indeed, there remain only the load changes. For the wire these variations are principally due to changes in the stock, the vacuum and the dry content, all of which affect the admissible stretch limit at the pick-up point. In most cases, though, these changes in the properties of the stock are greater than the changes in speed which are experienced.

The frequency response of the control system must be made such that the preferred oscillation frequency of the controller is perfectly mastered. Optimum conditions are reliably obtained when the fault in the paper machine is eliminated, because inadmissible stretch can also occur at absolutely constant speed. Despite the uncertain conditions in the paper machine, a study of the necessary accuracy of speed regulation should give some idea of the requirements.

The stretch between two sections of the machine is given by

$$\varepsilon = \frac{v_2 - v_1}{v_1} \quad \text{or} \quad \frac{v_2}{v_1} - 1$$

where v_1 and v_2 are the speeds of the first and second section, respectively, provided there is no preliminary stretch by the sheet entering the first section, the speeds are constant during the interval considered, and there is no technological stretch or shrinkage.

At the wet end a variation by up to ± 10% of the set stretch ought to be permissible. As mean value for the stretch between these sections we may assume a figure of about 4%. Thus the stretch can vary by up to ± 0·4%. If we also assume that both sections operate with the same accuracy, they must maintain their speeds constant to within ± 0·2%.

With increasing speed it becomes increasingly difficult to transfer the paper to the first press. In high-speed machines it is therefore customary now to employ a system of automatic pick-up (Fig. 6). The wire extends beyond the end of the paper sheet and is driven by a forward drive roll. The sheet is picked up off the wire between the couch roll and the forward drive roll by the felt running round the pick-up roll. In this way the difficulty of transferring the sheet is overcome, the sheet experiencing its first unsupported transfer between the first and second or between the second and third press.

In the presses the effects of the scatter bands of the stock and vacuum are smaller. The maximum change in load is experienced during threading-in the web, when changing over from strips to the full width. Here current changes of 50% can occur in 3–5 s. In addition, rapid changes are also possible due to variation of the nip pressure.

Normally the stretch between the presses amounts to 1–2%, the dry content on leaving the presses being 33–40%. If the same conditions are implied for the tolerance in the stretch, the speed of each section must be regulated to within ± 0·05 to 0·1%, or in other words the relative speed may change by 0·1 to 0·2% at the most.

The conditions at the end of the drying process in the dry end of the machine are quite different. Here the paper can be 80–94% dry, and the elongation on breakage drops to 1–2%. Most paper manufacturers stipulate a slight amount of slack between drying sections. In this case the paper does not stretch, apart from that due to its own weight and the effects of air currents. Owing to the restricted distances of sag, however, the conditions with respect to the co-ordination of the speeds are very strict, as the following considerations will show. Assuming the minimum sag $\vartheta_{min} = 5$ cm (Fig. 7) and the maximum $\vartheta_{max} = 11$ cm are permitted, the arrangement shown in Fig. 7 results in a theoretical change in length of the paper sheet of $\Delta s = 2$ cm. On a medium-speed machine with $v = 300$ m/min and a motor speed of $n = 1500$ rev/min, this would result in an admissible angular displacement between the two driving motors of

$$\alpha = \frac{n \cdot 360}{v} \cdot \frac{\Delta s}{100} = \frac{1500\,.\,360\,.\,2}{300\,.\,100} = 36^\circ$$

while for a high-speed motor with $v = 900$ m/min α becomes 12°.

In contrast to the wet end, therefore, the distance travelled by the paper sheet, i.e. the angular displacement of the motor axes, must be taken into consideration. However, measurements have proved that, despite the sag of the paper, there is still a certain amount of stretch, which decreases as the sag grows. Nevertheless this gives some idea of the order of magnitude of the requirements regarding angular accuracy of the drive.

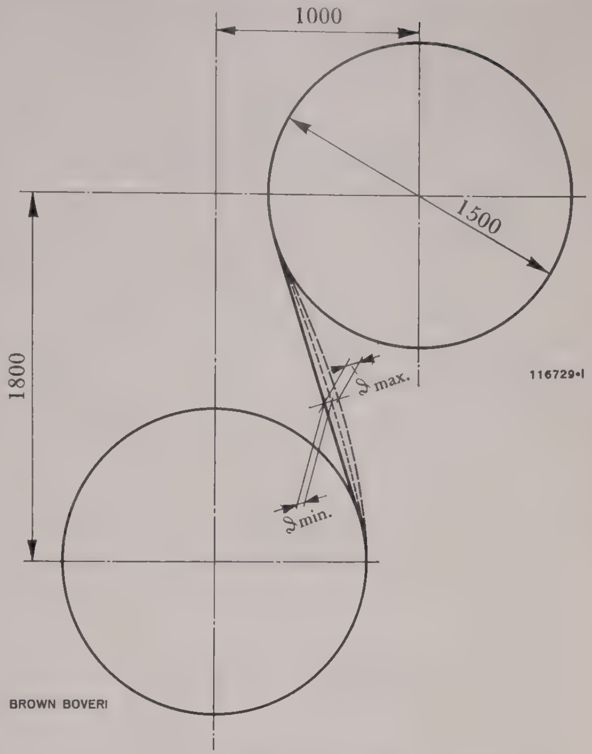


Fig. 7. – Course followed by the paper at the dry end

Quite different conditions are imposed on the drive of the calender, where the behaviour during threading-in is rather different to that during operation. Supposing we consider the length able to support itself and the breakage point of the paper at this point. For newsprint with a self-supporting length of 3000 m, i.e. with a tensile strength of $F = 150$ kg per metre width, this tension on a machine with a wire width of $b = 6$ m and a speed of $v = 750$ m/min, would require a motor rated

$$P = \frac{v}{60} \cdot \frac{F \cdot b}{102} = \frac{750\,.\,150\,.\,6}{60\,.\,102} = 110 \text{ kW}$$

In addition to this a power of about 130 kW would be required to overcome friction and for the work of calendering. If this range could be utilized in its entirety, a simple system of current control would be adequate. But speed control would also meet the requirements in every respect, because under these circumstances the elongation at break amounts to 1–2%, depending on the dry content. Unfortunately experience demonstrates that the change in draw is in reality much smaller. Obviously allowance must be made for a very uneven distribution of the tension across the width of the paper, and moreover it is evident that the tension in the paper has to possess a very definite magnitude on entering the calender. With machines of the size given above the ideal pull may only be 10% of this figure, and the tolerance only ± 5%. If these figures are related to the example given earlier, the power would be (130 + 11) ± 5·5 kW, i.e. $P = P_o \pm 4\%$. Hence for a system of speed control the stretch would have to be regulated to within ± 0·005 – 0·01%.[1]

Conditions are more exacting though while the paper is being threaded through the rollers. A pointed strip of the paper is first guided down the centre of the rollers by an operator. But the paper does not always become taut when this point is picked up, and a certain amount of sag results. Assuming that, in the example considered, a loop 1 m long is produced, it would take about 80 s to take up the slack at the operational lead setting of 0·1%. But this is certainly not admissible. It should be possible to take up the slack in not more than 5 s, which corresponds to a lead of 1·6%. Thus during the first 5 s the calender must rotate with this lead, being retarded to the desired working speed after this time.

When changing over from the narrow strip to the full sheet width the current can increase by 300% owing to the increased calendering work. The control system must also keep the speed constant under these conditions.

Other disturbance values are the nip pressure in the calender and the effect of the paper tension from the reeler. If the reeler pulls the paper, this relieves the load on the calender, necessitating an immediate compensation. Furthermore, in this section, changes in the dry content and stretch can exert a very unfavourable influence.

Experience gained with high-speed machines shows that appreciable wastage is often caused by difficulties in the calender. An analogy with everyday life may be made by comparing this section with a pair of heavy lorries tied together with a piece of string. These two lorries have to be driven along a road at, say, 45 km/h without the string breaking or becoming slack.

On the reeler the tension in the paper compared with the motor output is considerably larger than on the calender. On the other hand a loop must be picked up after it has been wound on. In steady-state operation the correct solution is to control to constant torque.

Drive Speed

As mentioned earlier, mains fluctuations must not be allowed to affect the drive of a paper machine. The object of this stipulation is not only to maintain the specific weight of the paper, but also to comply with certain dynamic conditions. As a rule, the specific weight of the paper varies much more than the working speed of the machine. The reasons for this are to be found on the technological side. Not only for the two forms of sectional drive, but also for the drives with shaft transmission, the working speed must be kept within certain limits. On a belt drive the slip at rated torque can be 1–2%. As a result of a mains fluctuation, causing a change in speed of the transmission shaft, the various sections would soon lose their synchronism, owing to their different rotating masses. But they are prevented from doing so by the belts. This causes a change of torque in the various sections of the machine, the result of which is that the slip can become positive in sections having a large rotating mass. The change in tension between heavy and light sections can thus assume quite large proportions, depending on the amount by which the speed of the shaft changes. On modern shaft drives the slip caused by the load has become very much smaller, but is nevertheless still present. This drawback can be largely overcome by rapid and accurate control of the working speed.

Mains fluctuations comprise changes in the voltage and the frequency. Assuming, for example, that a paper-mill is fed from a very powerful network via a transformer; owing to the reactance of the transformer it is possible for reactive load surges to cause voltage changes, which are transferred to the supply of the paper machine (Fig. 8). In contrast to frequency changes, voltage changes can occur quite suddenly, no control system being capable of preventing the first peak. If we assume that the paper-mill depicted in Fig. 8 contains a machine with an hourly output of 17 t of paper, the total power consumption of the factory would amount to about 29 000 kW.[2] If the same mill has a grinder motor rated 2000 kW, with a reactance of 20% on starting, and this motor were to be switched direct-on-line, this would cause a voltage drop of 3·6% to be produced at the short-circuit reactance of the transformer, allowing 10% for the latter. This assumes that the mill is supplied from a very large, powerful network, which may almost be treated as an infinite bus. Now the influence of a voltage change of this order depends largely on the manner in which the drives are fed. For instance, when the converter is driven by a synchronous machine, this change does not have any effect; with an induction motor, on the other hand, the speed changes with the square of the voltage. In the case of motors fed through rectifiers, the voltage change is transmitted direct to the motors. In such cases the need for rapid voltage control is obvious. The changes in the voltage under normal circumstances are usually about ten times as large as the changes in the frequency of the same network.

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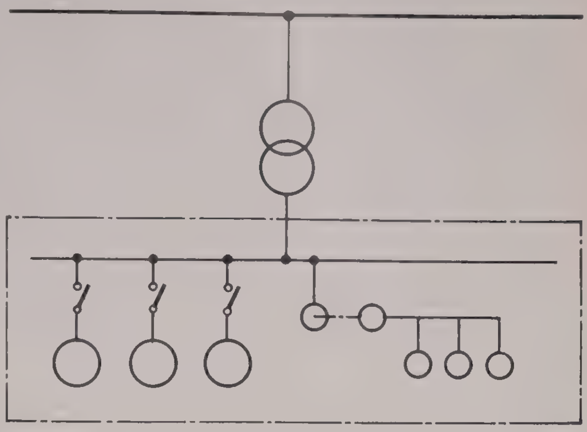
[1] $\varepsilon = \frac{\varepsilon_B\%}{1000} \cdot \frac{5}{100} = \frac{1\text{–}2}{1000} \cdot \frac{5}{100} = 0{\cdot}005 - 0{\cdot}01\%.$

[2] According to J. v. LASSBERG: Wärmewirtschaft in der Zellstoff- und Papierindustrie. Springer Verlag, Berlin 1926.



BROWN BOVERI 116730-I

Fig. 8. – Supply diagram of a paper machine

Left: Grinder motors
Right: Paper machine

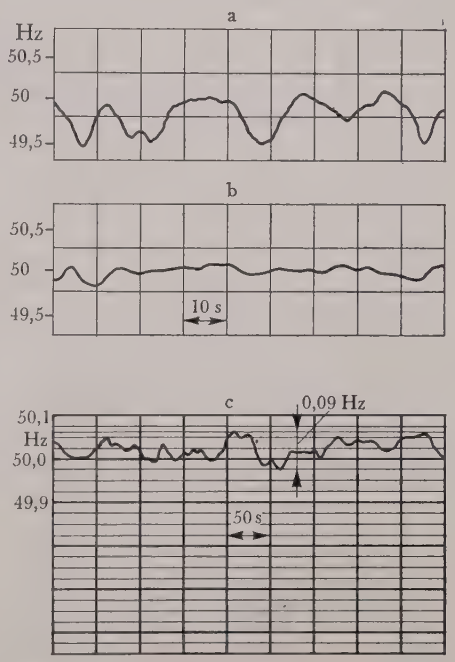


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Fig. 9. – Charts showing the variation of the mains frequency under different loading conditions in the system

a: System capacity 170 MVA, load mainly electric furnaces, with violently changing loading
b: Same system as in a, but with steadier furnace loading.
c: System with capacity of 1700 MVA

The fluctuation of the frequency in a network is very much less than the voltage changes, moreover it can never take place infinitely rapidly, because it is always associated with the acceleration or retardation of rotating masses. The rate of change is governed by the masses of the generators in the network. According to a report published by UCPTE (Union pour la coordination de la production et du transport de l'électricité) a change in frequency of 1 c/s should be admissible, taking into account the requirements of the consumers. On the other hand, having regard to the requirements of interconnected system operation, a much greater accuracy is stipulated, namely 0·1 c/s. Fig. 9 shows some typical frequency charts from power systems. Chart *a* was taken from a relatively small network with a total capacity of 170 MVA, in which electric furnaces had to be supplied. The maximum rate of change of frequency amounts to 0·16 c/s^2 with a bandwidth of about 0·6 c/s. The curve *b* shows the conditions in the same network when operation is somewhat steadier, i.e. when the furnaces are merely maintaining the temperature of the molten metal. Here the rate of change is only 0·07 c/s^2, while the bandwidth has diminished to 0·2 c/s. Conditions are still more favourable in a network with about ten times the capacity, where the frequency band only amounts to 0·09 c/s and the rate of change 0·01 c/s^2.

From the above considerations it is evident that, above all in networks with large voltage fluctuations and severe demands on the machines, supplying the latter through a converter offers certain advantages over rectifier feed, whereas in systems with greater frequency fluctuation and small voltage fluctuations equally good results can be achieved with rectifier feed and a rapid, accurate system of control.

Summary

The considerations show that a paper-machine drive has to comply with a number of different requirements. On the one hand it has to afford a certain degree of flexibility in the control, while, on the other, specific requirements are imposed on the paper tension and the working speed from the technological aspect, necessitating a detailed study of the system to be chosen. The arguments put forward in the article refer mainly to high-speed machines producing newsprint, but can easily be adapted for medium and small machines.

(KME) E. ANDRES

CONTROLLING THE WORKING SPEED OF PAPER MACHINES

676.2.052–83:621–531.6

This article is concerned with the methods devised by Brown Boveri and thoroughly tested in practice, for controlling the working speed of paper machines. The author takes into account slow-running and high-speed machines of modern design, as well as the various kinds of drives.

EXACT constancy in the working speed of a paper machine is important with respect to the following properties of the paper [1][1]: formation of the sheet, the specific weight of the sheet and the humidity. In addition, as will be explained later, the constancy of the working speed is also particularly important as regards maintenance of the draw between two successive sections of the machine.

The disturbance effects which may influence the working speed are:

Fluctuations in the supply of power, which are experienced as changes in voltage and frequency when connected to a three-phase system.

Changes in the load due to isolated sections of the machine being switched on or off, and due to changes in the stock input, vacuum, nip pressures, etc.

With increasing working speed, the effect of these disturbances on the quality of the paper also increases. The continual rise in the working speeds of paper machines consequently imposes increasingly severe requirements as regards the accuracy and rapidity of control. At speeds up to 600 m/min the well-established Brown Boveri quick-acting regulator can be employed with success; for higher speeds amplifiers and PID regulators (i.e. controllers with a proportional-integral-derivative action) based on electronic or magnetic principles and meeting the most exacting requirements.

Fundamentally, paper-machine drives may be divided into the categories with longitudinal transmission shaft and the sectional drives. In the latter case the individual sections of the machine are driven separately by their own motors, which are supplied from a common busbar system. This method is becoming increasingly popular, in fact for modern high-speed machines with large outputs it is the system most commonly used nowadays. For very high paper speeds, e.g. from 700 m/min, and when more exacting conditions are laid down for the control system, the multi-generator sectional drive may be employed with success, in which each drive section is equipped with its own generator. Depending on the drive system employed, either the voltage or the motor speed is utilized for regulation of the working speed.

Drives with Transmission Shaft

Drives employing steam engines have only been installed in a very small number of cases in recent years. The main advantages of this drive system,

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[1] The figures in brackets refer to the bibliography on p. 488.

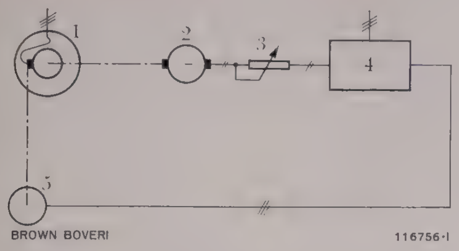

Fig. 1. – Circuit diagram of a drive with a shunt commutator motor and longitudinal transmission shaft

1 = Three-phase shunt commutator motor
2 = Tacho-generator
3 = Resistor for setting speed of paper machine
4 = PI regulator
5 = Servo-motor shifting brushgear of motor 1

namely low first costs, simple drive, absence of conversion losses, are offset by a number of drawbacks of an operational nature and associated with the control, as well as from the economical aspect: inability to dissociate the generation of power from the production of paper, dependence on the power produced in the actual factory, higher costs of maintenance, poorer efficiency when the speed of the turbine is governed, as well as the other well-known disadvantages of the shaft transmission; hence such drives are rarely employed and will therefore not be considered further in the present article.

A further, but seldom used method is the three-phase shunt commutator motor. Its advantages are the ability to connect the motor direct to a three-phase supply, thereby eliminating a converter and the associated losses. The drawbacks are: For speed ranges above about 1:3 the speed varies with the load, the efficiency remains at about the same level, but from the dynamic aspect speed control is not so good as with a d.c. drive. Hence the shunt commutator motor is only suitable for relatively small and slow-running machines, which do not impose any extreme conditions on the control system.

Briefly the principle of the control system may be explained as follows, with reference to Fig. 1. The speed of the shunt commutator motor 1 is measured by the tacho-generator 2. The voltage generated by the latter is conveyed via the rheostat 3, used to set the working speed, to the controller 4. Formerly the latter used to be an electro-dynamic pulse-type controller with proportional-integral (PI) action, and was employed in conjunction with contactors. When a deviation from the desired value occurred, this controller imparted pulses to the motor 5, and corrected the speed by shifting the brushgear. Nowadays this is performed by an electronic controller which continuously acts on a servo-motor.

In by far the majority of cases the transmission shaft is driven by one or two d.c. motors running in parallel. These motors may be fed from rotating converters or mercury-arc rectifiers.

The working speed can be controlled by either of the following methods:

> The speed of the drive motor is measured and compared with the set value (speed control).
>
> The armature voltage of the drive motor is utilized as a measure of the working speed (voltage control).

Voltage control offers the advantage that fluctuations of the mains voltage and frequency are determined in the d.c. voltage and can be corrected before they have time to exert a marked influence on the speed. But in dynamic phenomena the voltage and speed are not proportional, owing to the inertia of the rotating masses; moreover in steady-state operation differences may occur at different loads, owing to back-e.m.f. in the armature, which cannot be completely eliminated by compensation. Consequently the armature voltage is not an exact measure of the working speed.

Therefore, for longitudinal shaft transmissions, Brown Boveri prefer speed control because it permits all deviations from the set machine speed to be determined precisely. The slightly less rapid response to mains disturbances is made good by the employment of quick-acting, sensitive controllers and other measures, which will be dealt with later.

Supply by Rotating Converters

Let us first consider drives supplied by rotating converters. Here we may distinguish between Ward-Leonard circuits and the "buck-and-boost" circuit. With the Ward-Leonard drive the speed is set and controlled via the motor voltage, by varying the excitation of the generator in the desired limits.

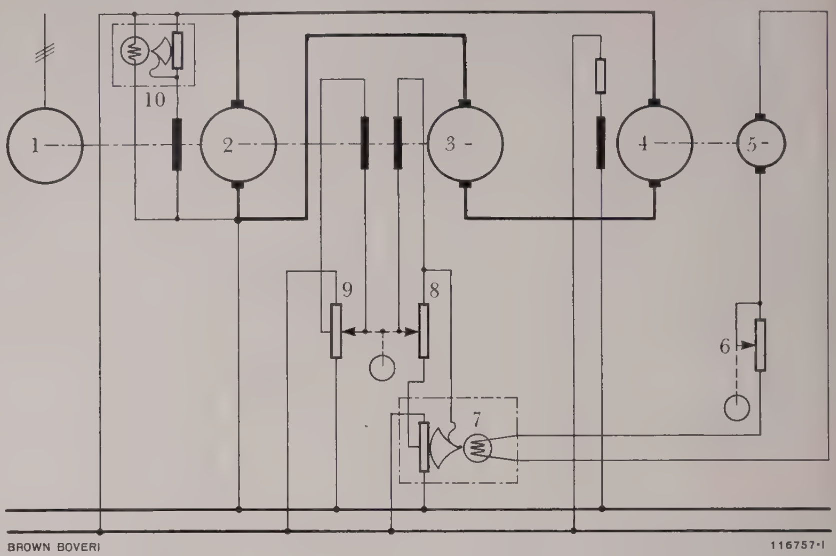

Fig. 2. – Circuit diagram of a drive with longitudinal transmission shaft and buck-and-boost generator; speed control by voltage regulator

1 = Three-phase motor
2 = Constant-voltage generator
3 = Buck-and-boost generator
4 = Motor driving the paper machine
5 = Tacho-generator
6 = Resistor for setting speed of paper machine
7 = Regulator for buck-and-boost voltage
8 = Resistor for setting regulator influence
9 = Changeover field rheostat
The resistors 8 and 9 are adapted to the position of 6 by a system of follow-up control
10 = Regulator for the constant voltage

The buck-and-boost circuit employs two generators, the first of which runs at constant voltage while the second (the buck-and-boost generator) produces a variable positive or negative voltage, which is either added to or subtracted from the constant voltage.

The question of whether the Ward-Leonard drive or the buck-and-boost circuit is preferable in a particular case must be individually investigated, because allowance has to be made for a variety of technical and economical factors. Fundamentally the following may be stated:

The Ward-Leonard system offers advantages because it employs only one machine and its circuitry is much simpler. The buck-and-boost circuit allows the machine to continue running in the event of one generator failing. At low working speeds the disturbance influences without control are less than with the Ward-Leonard system. On the other hand control with a good dynamic response requires more outlay for the buck-and-boost circuit.

Fig. 2 shows the principle for speed control, which has been employed for close on fifty years for small and medium machines with speeds up to 400 m/min. Supply can be by a Ward-Leonard generator or, as shown in Fig. 2, by a buck-and-boost generator.

The three-phase motor 1 drives both the constant-voltage generator and the buck-and-boost generator, the latter having two field windings. The speed of the motor 4 driving the paper machine is converted into a proportional voltage by the tacho-generator 5. This voltage is applied to the measuring system of the controller 7 via the setting resistor 6. The controller feeds the supplementary field of the buck-and-boost generator 3. The basic field is positively or negatively excited via the changeover field regulator, depending on the position of the latter. To adjust the working speed, the setting resistor 6 is first adjusted by means of its motor.

This resistor varies the effect of the tacho-generator voltage on the controller according to the set working speed. A system of follow-up control displaces the changeover resistance, thereby bringing the basic field of the buck-and-boost generator, and with it the supply voltage of the motor, to the desired value. Coupled with the changeover resistor is a resistor 8, which adapts the influence of the controller to the new working speed. Thus control is uniform over the entire speed range. A further speed regulator 10 prevents the output of the constant-voltage generator from varying. When a Ward-Leonard generator is employed the circuit is modified as

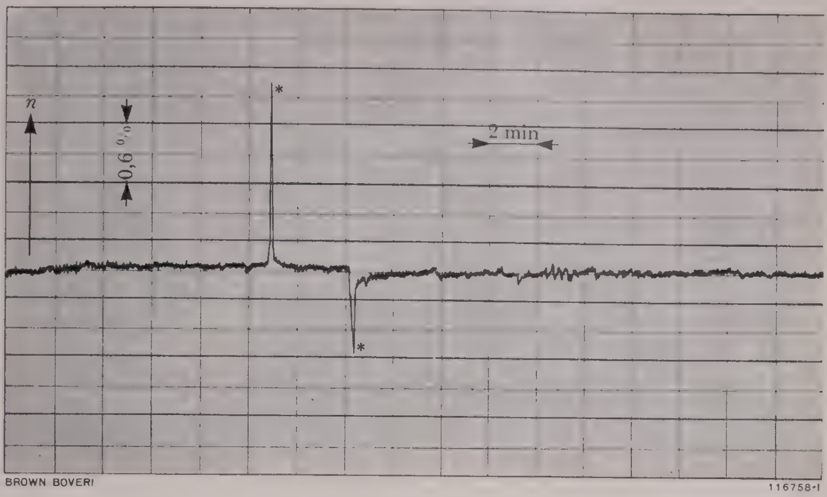

Fig. 3. – Working speed of a paper machine with longitudinal transmission shaft; speed control by voltage regulator

Data of the paper machine:

Wire width 3200 mm, speed 20–200 m/min, input 315 kW, speed when trace recorded 80 m/min (quantity measured: speed *n* of the transmission)

Product: writing paper, 60 g/m²

* Regulator displaced by hand

shown in Fig. 4. The changeover resistor 9 is replaced by an ordinary field rheostat; since only one generator is used, the voltage regulator 10 can be dispensed with.

For a machine with a power input of 315 kW, a wire width of 3200 mm and a speed range of 20–200 m/min, a record was made of the working speed (Fig. 3). To test the dynamic response, the controller was displaced by hand. The manner in which the deviation is corrected, with no residual error, is obvious at a glance.

The sensitivity is considerably improved if a frequency regulator is employed instead of the voltage regulator. Fig. 4 shows the circuit for speed control with a frequency regulator. In the place of a tacho-generator, a frequency generator 4 is coupled with the paper-machine motor 3. The generated frequency is a measure of the speed which, with the aid of the frequency-dependent network (choke 5 and capacitor 6), is measured by the regulator 7 and compared with the set value. The setting in this case is the resonant frequency of the choke and capacitor, whereas normally a resistor provides the setting, as in Fig. 2. The regulator acts on the Ward-Leonard generator 2 through an exciter 8. On account of its high sensitivity this circuit is employed for high-speed paper machines with speeds up to about 600 m/min. It is suitable for speed ranges of 1 : 3, or still higher when changeover facilities are provided.

The traces in Fig. 5 were recorded on a machine producing paper with a specific weight of 40–90 g/m², having a wire width of 4500 mm, a power input of 1300 kW and a speed range from 250 to 600 m/min. Fig. 5a shows the speed of the paper machine when power is drawn from the general supply network. The mean steady-state accuracy, as measured, is ± 0·05%. Fig. 5b was recorded when the machine was being supplied by the factory's own power system. Here frequency

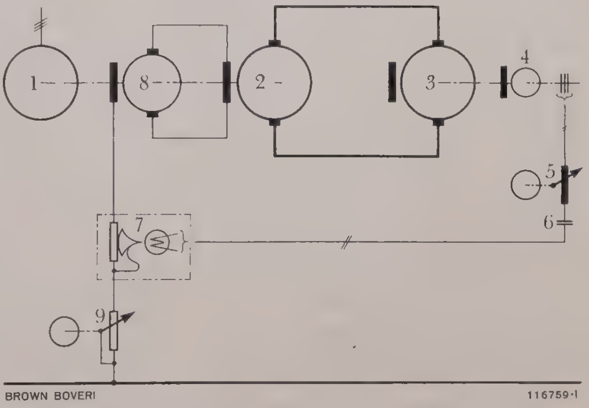

Fig. 4. – Circuit diagram of a Ward-Leonard drive with longitudinal transmission shaft: speed control by frequency regulator

1 = Three-phase motor
2 = Ward-Leonard generator
3 = Motor driving paper machine
4 = Frequency generator
5 = Choke for setting speed of paper machine
6 = Capacitor
7 = Frequency regulator
8 = Exciter
9 = Setting resistor, adapted to position of 5 by follow-up control

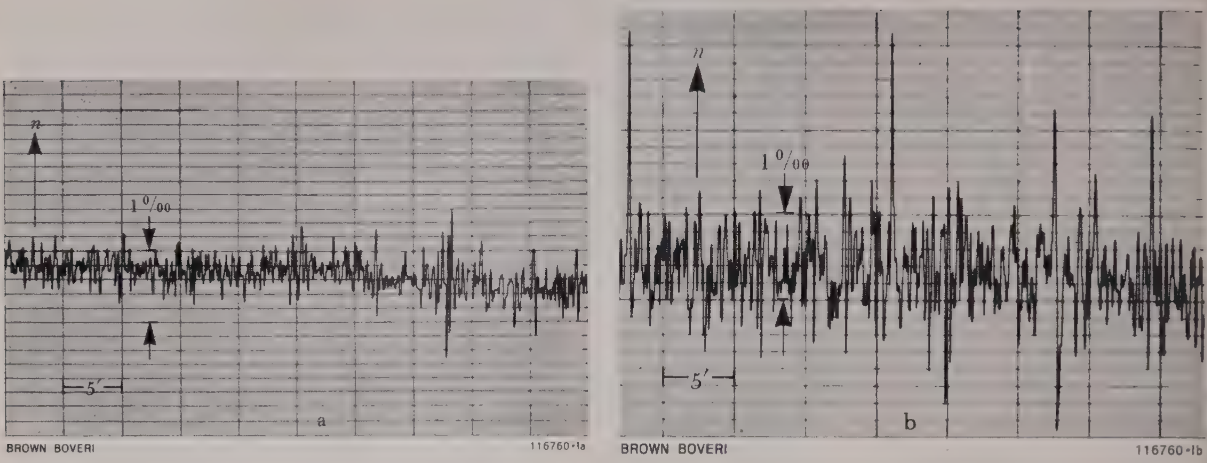

Fig. 5 – Working speed of a paper machine with longitudinal transmission shaft: speed control by frequency regulator

a: Supply from general mains

b: Supply from factory network with frequency fluctuation of 1·6% and rate of change of 0·1 c/s²

Data of the paper machine: Wire width 4500 mm, speed 250–600 m/min, input 1300 kW, speed when trace recorded, 340 m/min; quantity recorded was *n*, the speed of the transmission.

Product: paper glazed on both sides, 80 g/m².

fluctuations of 1·6% were measured at a rate of 0·1 c/s². The maximum deviation of the speed of the paper machine under these conditions amounted to ± 0·18%.

For the two circuit arrangements described the Brown Boveri rolling-sector regulators were used, which have proved successful for over 50 years. They function reliably, are not subject to wear, and therefore require no maintenance. Their response can be largely adapted to the prevailing conditions. In the circuits referred to these regulators are employed with a PI action; within certain limits it is also possible to incorporate a small derivative action.

For more exacting requirements, as with modern paper machines, especially for very high working speeds, it becomes necessary to employ electronic and magnetic regulators and amplifiers. With speed control stable operation can only be assured with a PI controller up to a certain control speed. For more rapid control the derivative influence of the controlled variable must be applied to the controller. Modern electronic controllers, as well as those containing magnetic amplifiers, therefore have a PID action, rendering them universally applicable.

The relationship between speed of control and stability can be demonstrated most forcibly by the Bode diagram of the opened control circuit.[2] For stable operation it is essential for the ratio $|F_R|$ of the amplitude of the output to the input of the control loop at zero response and in the vicinity thereof not to decrease more rapidly than 20 db per decade change in frequency. Fig. 7 shows the schematic appearance of the frequency response diagrams for speed control with the circuit in Fig. 6, on the one hand with a frequency regulator with PI action (Fig. 7a), and on the other with a magnetic amplifier controller with PID action (Fig. 7b). The broken line 1 in Fig. 7a shows the frequency response of the controlled object (exciter, generator, drive motor), the full line 2 applying to the complete opened loop (controlled object + controller). To ensure stability, the gain of the controller must be reduced, which is expressed by a downward displacement of the frequency response.

Fig. 7b applies to the same circuit with a PID controller. Owing to the derivative action, an appreciable drop in the frequency response when the generator time constant comes into effect is prevented, and the zero point shifted to the right in the region of rising frequency.

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[2] See, for instance, Brown Boveri Rev. 1959, Vol. 46, No. 11/12, page 603.

Fig. 6. – Circuit diagram of a drive with transmission shaft and speed control by electronic or magnetic PID controller and amplifier

1 = Three-phase motor
2 = Ward-Leonard generator
3 = Motor driving paper machine
4 = Tacho-generator
5 = PID controller
6 = Amplifier
7 = Means of setting the desired speed of the paper machine

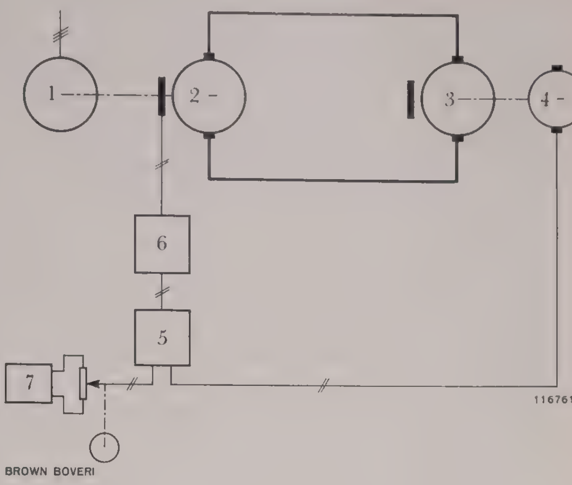


Fig. 7a. – Frequency response of speed control with PI controller (frequency regulator as in Fig. 5)

1 = Frequency response of the controlled object consisting of exciter, generator, drive motor with rotating masses of paper machine

2 = Frequency response of the overall control circuit, comprising the controlled object as in 1 plus the frequency generator and frequency regulator

$|F_R| = 20 \log \left|\frac{\text{output}}{\text{input}}\right|$ in db

ω_c = Frequency at zero response
T_m = Starting time constant of motor (with rotating masses)
T_g = Time constant of generator
T_e = Time constant of exciter

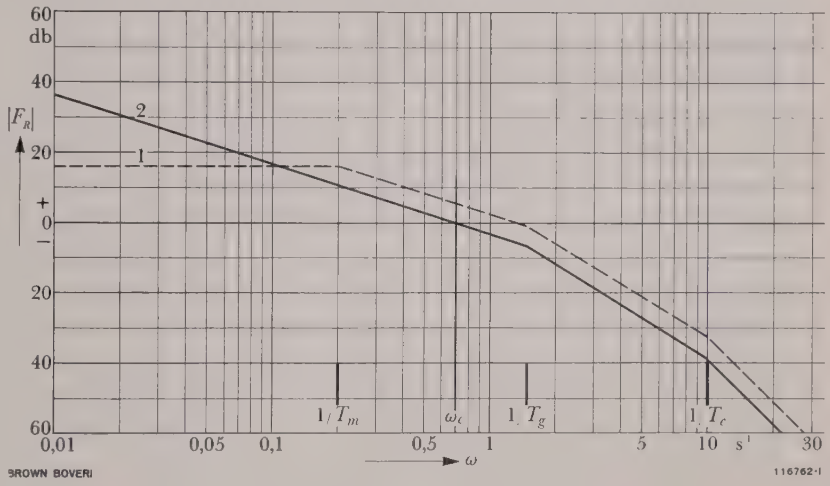
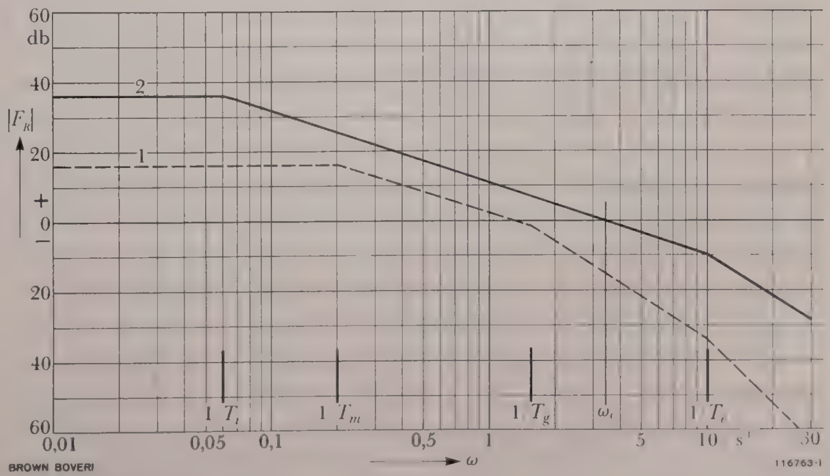


Fig. 7b. – Frequency response of a speed control system with PID controller (magnetic amplifier controller and amplifier, circuit as in Fig. 6, but with additional exciter)

1 = Frequency response of the controlled object, comprising exciter, generator, drive motor with rotating masses of the paper machine

2 = Frequency response of the entire controlled circuit, comprising the controlled object as in 1, plus the tacho-generator, the PID controller and the magnetic amplifier



T_i = Integral action time of the PID controller

Other notations as for Fig. 7a

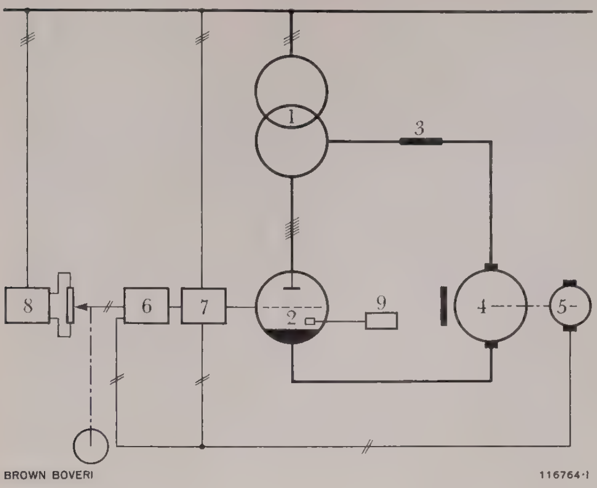


Fig. 8. – Circuit diagram of drive with transmission shaft, fed by mercury-arc rectifier

1 = Transformer with six-phase secondary
2 = Mercury-arc rectifier
3 = Smoothing choke
4 = Motor driving paper machine
5 = Tacho-generator
6 = Electronic PI controller
7 = Grid control set
8 = Means of setting desired speed of machine
9 = Starting unit

It will be observed that both frequency responses are stable. The time T_R taken to correct a disturbance is given approximately by the formula

$$T_R \approx \frac{\pi}{\omega_c}$$

According to this, the settling time in Fig. 7a with a PI controller is

$$T_R \approx 5 \text{ s}$$

while with a PID controller this time is reduced to

$$T_R \approx 0{\cdot}9 \text{ s}$$

The above example is merely given to illustrate the fundamental significance of the PID controller. In practice the exciter can be replaced by a suitable amplifier with a shorter time constant. In this way the control speed and the gain in the closed loop can be improved, while retaining the same stability.

The high gain, the advantages referred to in the response of the PID controller, and the ability to employ elements with high measuring accuracy make it possible for a steady-state accuracy in the working speed of ± 0·1 to 0·15% to be maintained. The maximum, momentary deviations caused by disturbances amount to ± 0·2 to 0·3%, and these are corrected in an extremely short time.

If rotating converters are used to supply the drive motor, it is possible to prevent mains fluctuations from having any effect on the d.c. voltage by employing a synchronous motor. The speed of the converter is then only dependent on changes in frequency, whereas the speed of an induction motor varies with the square of the mains voltage. Since the frequency of large power systems generally varies much less and more slowly than the voltage, this eliminates an important source of disturbance. Moreover, the use of a synchronous motor also offers the advantage of being able to improve the overall power factor of the installation.

Supply by Mercury-Arc Rectifiers

For some time now mercury-arc rectifiers (mutators) have been used to supply paper-machine drives, the action of the arc converting the alternating input into a pulsating d.c. output. With the aid of the grid control system it is possible to vary the firing point of the rectifier in such a way that the rectified portion of the sinusoidal a.c. can be varied at will. In this way a d.c. voltage variable infinitely between zero and maximum is obtained for feeding the motor. The employment of tanks with six anodes, combined with a suitable connection of the supply transformer, reduces the ripple in the d.c. output, which is smoothed still further by a choke. The basic circuit arrangement of a rectifier-fed paper-machine drive is shown in Fig. 8. The three-phase transformer 1 with its polyphase secondary winding feeds the six anodes of the rectifier with voltages mutually displaced by 1/6 of a cycle in phase. The rectified current flows via the smoothing choke 3 to the drive motor 4. The voltage of the tacho-generator 5 is compared with the set value 8 and the voltage difference conveyed to the controller 6. In the grid control set 7 the firing pulses and the necessary negative grid bias are generated. In this case the controller determines the firing point, and thus the magnitude of the d.c. voltage.[3] The controller and the grid control set are purely electronic units and therefore operate almost instantaneously. Mains disturbances occurring at the controller input, or load changes, are corrected in a time of the order of 10 ms.

Rectifier feed may be considered for paper-machine drives from about 100 kW upwards. The susceptibility to disturbance by backfires is very slight in modern pumpless units. Compared with rotating converters, rectifiers require very little space, lighter foundations and less maintenance. The efficiency of a mercury-arc rectifier at half working speed is roughly equal to that of a rotating converter. In the upper part of the range it is slightly better, but at the lower end it gradually depreciates as the speed is reduced. The power factor is very dependent upon the working speed and varies almost linearly with it. Improvement can be effected by varying the transformer voltage with the paper speed, for instance by changing over from delta to star for the lower part of the range. This change, however, means that operation has to be interrupted.

Sectional Drives

Modern paper machines with a longitudinal transmission shaft are also equipped with up to 20 electric motors known as helper drives. The consistent pursuit of this tendency leads to the sectional drive in which each section of the machine is driven by a separate motor. Modern requirements for the control can only be fulfilled mechanically with a considerable outlay, for instance using differential gears, in most cases exceeding the cost of a sectional drive. Consequently nowadays large machines are equipped exclusively, medium machines for the greater part, with sectional drives; even with small machines the advantages of this kind of drive can become so pronounced that a sectional drive is often chosen. The individual advantages are dealt with in detail in the article beginning on page 469. For sectional drives not only the working speed has to be controlled, but also the relationship of the various section speeds (draw) to one another. This is performed, for example, by comparing frequencies proportional to the motor speeds, with a common master frequency, using sensitive electrical differentials, see page 489–500. The exact constancy of the set working speed is also extremely important as regards the precise maintenance of the tensions in the paper, as may be illustrated by the following remarks:

In an uncontrolled drive a drop in frequency of 2% in the mains supply, i.e. of the order of 1 c/s, such as can be expected in factory networks, produces an equally large drop in the working speed referred to the rated speed n_n. Owing to the different rotating masses in the various sections, they do not follow this change at the same rate. Until the new steady condition has been attained, it is possible for appreciable deviations from the set speed relationships to have occurred [2]. If, for example, the last press has a time constant of $T_1 = 14$ s, and the succeeding drier $T_2 = 80$ s (these are the time constants for starting at rated torque), and if the speeds were equal before the disturbance, i.e. $n_1 = n_2 = n_n$, the speed difference which will occur will be

$$\frac{n_2 - n_1}{n_n} = \frac{\Delta n}{n_n}\left(e^{-t/T_2} - e^{-t/T_1}\right)$$

With the figures given above, a maximum difference of more than 1% occurs after about 30 s. To prevent such disturbances from affecting the system, the busbar voltage of all motors is controlled for sectional drives. In the event of mains disturbances there is no need for the draw control to intervene.

The motors of a sectional drive can be supplied in the same manner as a single-motor drive. There are therefore sectional drives using shunt commutator motors, and others with d.c. motors fed by rotating converters or rectifiers. The properties of the various kinds of drives mentioned in reference to drives with longitudinal transmission shaft apply equally to sectional drives.

To control the busbar voltage of d.c. drives, the same systems are employed as for controlling the speed with shaft transmission. The measuring system of the controller may be connected directly

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[3] Since the mercury-arc rectifier has no time constant like the d.c. generator, it is sufficient to employ a controller with P action.

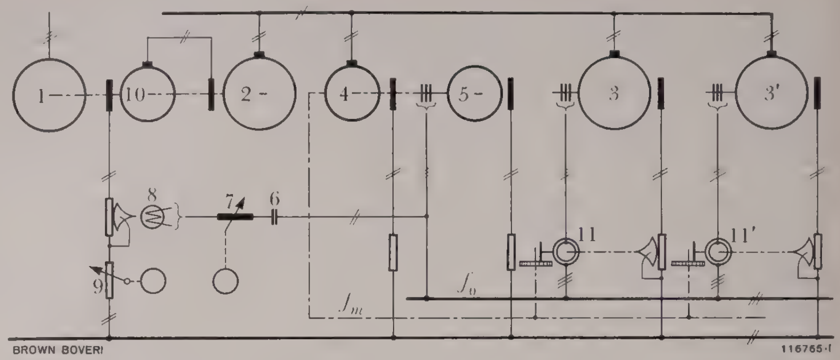

Fig. 9. – Sectional drive supplied from busbar system: speed control by frequency regulator

1 = Three-phase motor
2 = Ward-Leonard generator
3, 3′ = Motors driving sections of paper machine
4 = Master motor
5 = Generator of master frequency
6 = Capacitor
7 = Choke for setting speed of machine
8 = Frequency regulator
9 = Setting resistor, adapted to position of 7 by system of follow-up control
10 = Exciter
11, 11′ = Draw regulators for section drives
f_0 = Electrical master frequency
f_m = Mechanical master frequency

or indirectly to the voltage. Since, with voltage control, the rotating masses do not enter into the controlled object, controllers with PI action are perfectly capable of maintaining stability at high speeds of control.

Here too the method used for voltage control is that shown in Fig. 2. When a frequency regulator (Fig. 9) is used, an additional motor known as the master motor 4, fed from the busbars, is used to drive the generator 5 for the master frequency. The frequency regulator 8 keeps this value constant, according to the value set on the choke 7. Since the rotating mass of the master section is small compared with that of the section drives of the paper machine, every mains disturbance is detected and corrected before it has time to exert a noticeable influence on the speed of the section drive.

For more exacting requirements electronic and magnetic controllers and amplifiers are also used with sectional drives. Owing to the high gain and the short time constants of these elements, the desired accuracy can be attained simply with a proportional action, provided suitable feedbacks are provided for stabilization. The feedbacks are in most cases the differential quotients of the busbar voltage, and perhaps the exciter voltage. When a PID controller is used there is no need for external feedbacks, because the desired response can be set on the controller itself.

The results obtained with the circuits listed, as regards accuracy and speed of control, are the same as for drives with a longitudinal transmission shaft.

Multi-Generator Sectional Drives

For some time it has been common practice to provide two converters for large paper machines, one for the motors driving the wet end, the other for the dry end. The advantages thereby gained, especially during manoeuvring (see pages 469–78), logically developed into the multi-generator drive, in which each drive section has its own generator. This form of drive is particularly suitable for large, high-speed newsprint machines and is becoming increasingly popular. The advantage of this drive from the control aspect is that changes in the speed can no longer be transmitted from one section to another via the busbars. A drawback is that load changes in one section affect the section generator more severely than they would with one generator supplying all motors. But this advantage is balanced by the fact that speed control is employed with multi-generator drives, enabling all deviations to be corrected.

To control the working speed there must first be a control circuit for each section generator (see pages 489–500), corresponding in principle to the system with the longitudinal transmission shaft. In addition, for all these control circuits a common reference value is required, which is generated and regulated in a separate circuit. The arrangement of this circuit is shown in Fig. 10. The master section, already indicated in Fig. 9, now has a generator of its own, known as the master generator 2, which is driven by a single three-phase motor common to all other section generators. The master generator feeds the master motor 3 which, in turn, drives the generator 4 for the master frequency, as well as an additional precision tacho-generator 5, providing a d.c. voltage acting as the reference value for all other section regulators. The master frequency, and thus the master voltage, is kept constant at the value set on choke 7 by means of a frequency regulator 8. Apart from the frequency regulator, a magnetic amplifier 10 also acts on the master generator. The task of this amplifier is to correct major supply fluctuations before they can affect the speed of the master section. In this manner the master frequency and master voltage are regulated with great accuracy, as shown by a chart (Fig. 11) recorded in service. An article in an earlier issue of this journal [3] reported on the excellent control properties of this master circuit. The charts show the variation of the master voltage, mains frequency and the position of the frequency regulator of a machine producing newsprint at a maximum speed of 750 m/min, with a wire 7366 mm wide and a total input of 2800 kW. The factory supply network was subject to frequency fluctuations of ± 0·4 c/s, i.e. ± 0·8%. In spite of this relatively large fluctuation, the frequency regulator had only

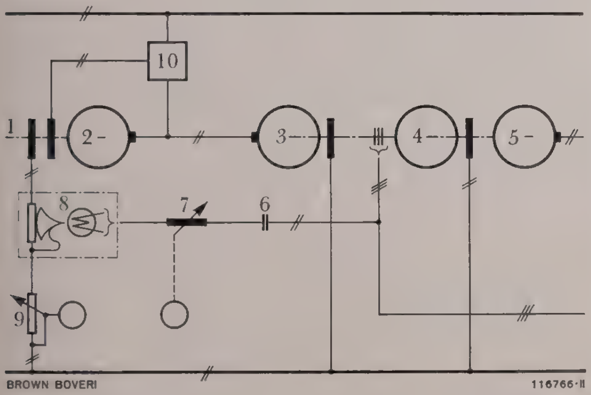

Fig. 10. – Circuit diagram of control of the master section with multi-generator sectional drive

1 = Shaft of converter set
2 = Master generator
3 = Master motor
4 = Generator for master frequency
5 = Generator of master voltage
6 = Capacitor
7 = Choke for setting speed of machine
8 = Frequency regulator
9 = Setting resistor, adapted to position of 7 by follow-up control
10 = Magnetic amplifier to correct voltage fluctuation by master generator

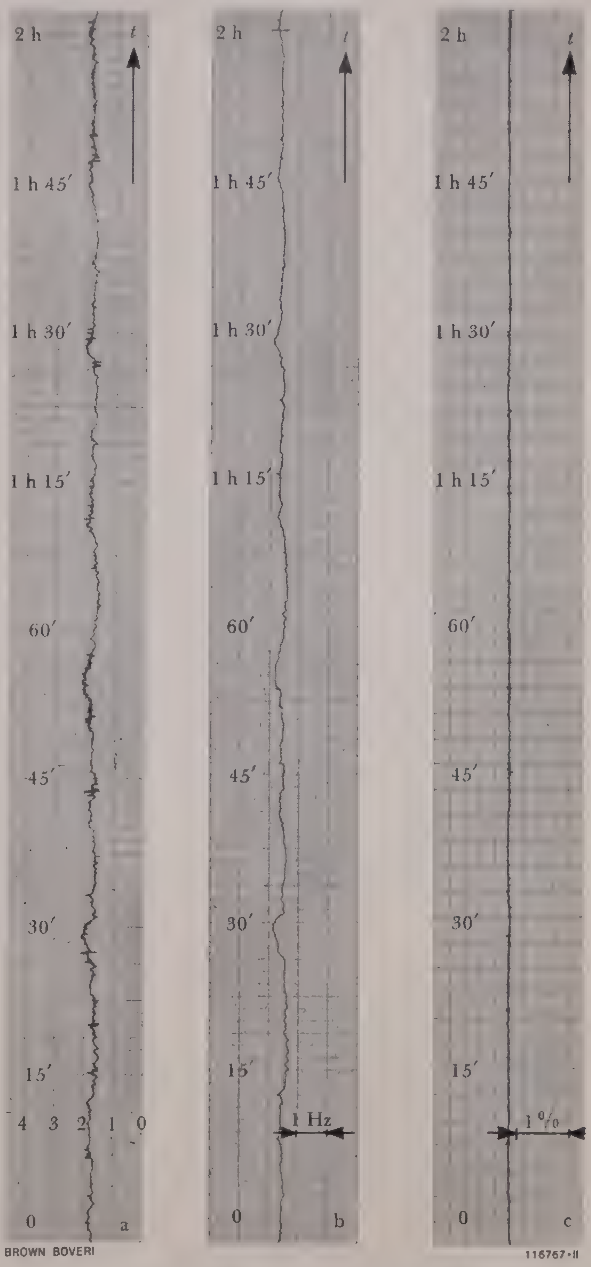

Fig. 11. – Working speed of a newsprint machine with multi-generator sectional drive

Data of the paper machine: Wire width 7366 mm, speed 250–750 m/min, input 2800 kW, traces recorded at a speed of 550 m/min. Product: newsprint 50 g/m². *t* = time scale.

a: Position of frequency regulator
b: Frequency of factory supply network
c: Master voltage

to intervene to quite a small extent, because the magnetic amplifier largely prevented the mains disturbances from affecting the master section. For the master voltage during dynamic phenomena the maximum deviations measured were ± 0·08%. The steady-state accuracy amounted to about ± 0·04%.

Conclusions

In conclusion, reference may be made once more to the effect of the different drive systems and the converters on the control. The increasing tendency to adopt the principle of individual drive has led from the transmission shaft to the sectional drive, and from there to the multi-generator sectional drive. This development admittedly involves greater outlay, but it does strictly localize any faults which may occur, provided they were caused by the paper machine. With rotating converters the effect of mains fluctuations on the d.c. voltage is somewhat retarded by the rotating masses. When a synchronous motor is used to drive the converter fluctuations in the mains voltage can be prevented from having any effect. When rectifiers are used for the supply, mains fluctuations affect the d.c. output almost instantaneously, so that extremely rapid control is essential.

Based on the advantages mentioned, Brown Boveri adopt the system of speed control in the majority of cases. For very exacting demands regarding the accuracy and speed of control, the system known as the multi-generator sectional drive was devised, which combines the advantages of voltage control with those of speed control, so that mains fluctuations are largely corrected before they can affect the speed.

The choice of drive and converter is governed to a large extent by economical and technological factors. The aim of the foregoing article was to show that methods are available for controlling the working speed of the paper machine under all the circumstances considered, all of which have proved satisfactory in service and have fulfilled the most exacting conditions.

(KME) R. WENDT

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CONTROL OF THE INDIVIDUAL SECTIONS OF PAPER-MACHINE DRIVES

676.2.052–83:621–53

This article deals with control systems, from the very simplest to the modern cascade circuits, such as are used for high-speed machines. In particular busbar-fed sectional drives are discussed, as well as multi-generator drives with the motor supplied from its own generator in each section. The control and measuring systems, and their effects on the special operating conditions are dealt with in detail. The dynamic phenomena are explained with reference to frequency response equations. The special features of measurement and control of calenders and winders are also dealt with in full.

Requirements for the Drive

THE general increase in the demand for paper and the resultant growth in the production capacity have caused the manufacturers of paper machines to build larger and faster units. The increasingly severe requirements of course pose new problems for the electric drive equipment.

In the manufacture of paper a continuous sheet of paper is produced from wood pulp and cellulose fibres. The material running through the machine is subjected to predetermined elongation and tensile stresses at the various transfer points. It must, however, be remembered that the tension-elongation curve of a sheet of paper can assume a quite different shape, according to whether the paper is wet or dry. From technological considerations a definite elongation, or stretch, is specified in each section of the process, and this must stay constant for days or weeks on end, regardless of external conditions. Over-stretching or shrinkage should be avoided as far as possible, in order that the quality of the finished product may not deteriorate. For this reason, and to eliminate varying stresses in the sheet, the requirements for the speed and accuracy of control on high-speed machines are particularly exacting.

Measuring the Stretch of the Paper Sheet

Since it is impossible to measure the stretch of the paper direct, e.g. with floating rollers, owing to the lack of strength of the sheet, and for mechanical reasons, the only possible method is to measure it indirectly.

A simple means of measuring the elongation of the paper is to use an electrical differential known as a synchroscope, which compares the speed of the section motor (expressed as a frequency) with a preset desired frequency. The principle of the synchroscope is illustrated in Fig. 1.

The electrical desired frequency f_0, common to all sections of the drive and supplied by a frequency generator, is applied to the rotatable stators of the synchroscope. The synchroscope is radially adjustable with respect to a runner, and its stators are driven by a friction-wheel with the mechanical

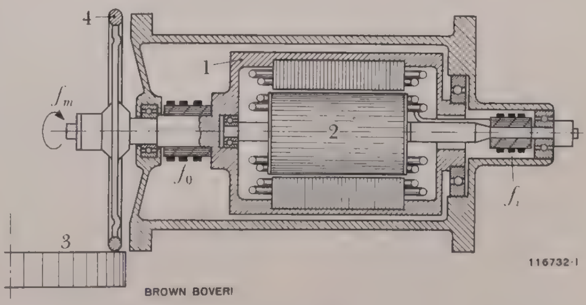

Fig. 1. – Design of the synchroscope used in the draw control system

1 = Stator (able to revolve)
2 = Rotor
3 = Runner of the draw regulator unit
4 = Friction-wheel
f_0 = Electric desired frequency
f_m = Mechanical desired frequency
f_i = Actual frequency of the section motor

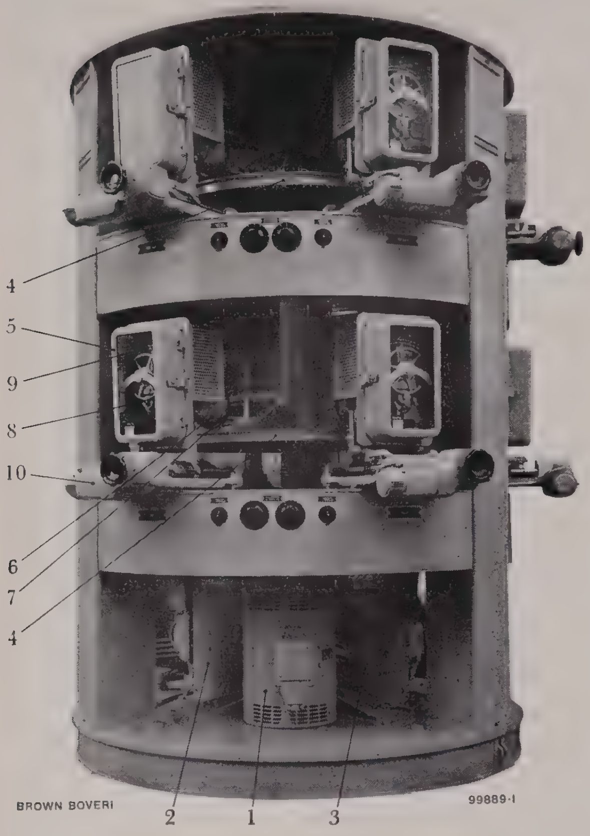

Fig. 2. – Unit containing built-in draw regulators

1 = Motor
2 = Master frequency generator
3 = Tacho-generator
4 = Runners
5 = Draw regulators
6 = Synchroscope
7 = Friction-wheel
8 = Rotor axis of synchroscope
9 = Rolling sector
10 = Adjustment mechanism with selsyn drive

frequency f_m. The rotating field of the stators therefore rotates in space with the frequency $f_0 + f_m$. By shifting the synchroscope in a radial direction relative to the runner, the value of f_m, or the stretch necessary in operation at that section, can be individually adjusted. The actual-value frequency f_i obtained from the slip rings of the section motor feeds the rotor of the synchroscope. When there is phase or frequency coincidence between f_0 and f_i, the rotor remains steady in its momentary position. A deviation causes the rotor to revolve with the frequency

$$f_d = f_0 + f_m - f_i$$

Frequencies can be measured very accurately, independent of all external variables, such as the contact resistance of the brushes or temperature rises, and a set value remains invariable with respect to time. The torque which the rotor has to impart to the correcting element (sector of the draw regulator) is extremely small, which explains why only very slight losses arise from the transmission from the runner to the friction-wheel. Moreover, since the frequency f_m is only a fraction of the desired frequency f_0, any error which happens to occur only affects the measurement to a fraction of its full extent. The contact area between the runner and the friction-wheel is very small, thus permitting a sensitive and clear adjustment of their relative positions (Fig. 2). Also the carefully selected material from which the friction-wheels are made ensures that they run precisely and free from slip. Using a digital system the coordination between a pair of synchroscopes was measured over a period of 5 hours (Fig. 3), during the course of which the maximum deviation measured was only 0·005%. By means of a special design and transmitting very small torques, the sensitivity of response of the measuring system at maximum frequency remains within an electrical angle of 4°. Referred to the motor this represents a relative displacement of 2° on four-pole machines, and 1·3° on six-pole.

For more exacting requirements the phase displacement between the desired and the actual frequency is determined by the synchroscope and the measurand transmitted mechanically to an induction regulator. A measurand transducer operating on the principle of the ring modulator provides a d.c. voltage proportional to the rotation (Fig. 4) [1].[1] The measurand transducer is composed of a three-phase bridge circuit consisting of one three-phase and three single-phase transformers with diodes controlled by the measured voltage. The manner in which such an arrangement functions may be gathered from the vector diagram (Fig. 4, right), which is only drawn single-phase for the sake of clarity. The alternating voltage $\vec{U}_M$ applied to the measuring circuit is superposed on the synchronous, but much larger auxiliary voltage in

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[1] The figures in brackets refer to the bibliography on p. 500.

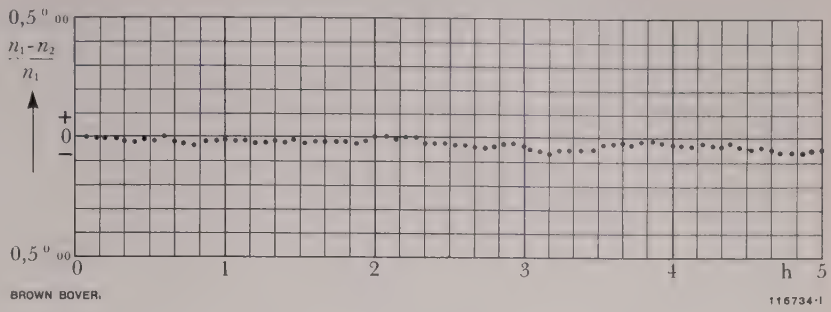


Fig. 3. – Digital speed measurement to compare two synchroscopes as a function of time

Readings taken every 4 min over a total of 5 h

n_1, n_2 = Speeds

the bridge circuit in such a manner that the sum $\vec{U}_H + \vec{U}_M$ is effective in one limb of the bridge, while the difference $\vec{U}''_H - \vec{U}_M$ is effective in the other. Thus on the bridge resistance R there is a pulsating d.c. voltage of the order of magnitude of $U_M \times 2$, provided the phase angle of the applied alternating voltage is zero. The output voltage varies with the cosine of the included angle φ. It depends on the magnitude of the measured voltage, but not on that of the auxiliary voltage.

A further easy means of measuring the stretch between two sections is afforded by the well-known system of speed control by tacho-generators, in which the deviation between measured and desired voltage is applied to an electronic or magnetic amplifier. Since tacho-generators and the usual means of setting the desired value do not comply with the severe accuracy requirements of paper machines, the advantages accruing from this measuring system, to be explained in the next chapter, are principally combined with orthogonal measuring systems.

As explained in the article beginning on page 469, the requirements with respect to the angular accuracy at the dry end of the machine are severe, for which reason a system of distance control, or a combination of speed and distance control is preferred. At the wet end though, where greater tolerances are admissible in the stretch, it may be feasible for speed control to be employed alone.

Design and Principle of the Control System with Busbar Feed

Field Control of the Motor with Draw Regulator

The simplest method of inserting the synchroscope in the control circuit is to couple the rotor with the correcting element (sector of the draw regulator), which is designed as a variable resistance, and to connect it in the field circuit of the motor (Fig. 5). The measuring and correcting elements are combined in a central unit referred to as the draw regulator, in which the transmission of the torque from the measuring element to the rolling sector is effected practically without losses. (Fig. 2). The action of the control system corresponds to a pure integral action. Consequently a speed deviation is corrected without leaving any residual error. For reasons of stability, however, the speed of adjustment is limited, which results in rather long settling times in the event of sudden disturbances. The block diagram of the control system is illustrated in Fig. 6. Fig. 7 shows the equivalent circuit diagram of the motor.

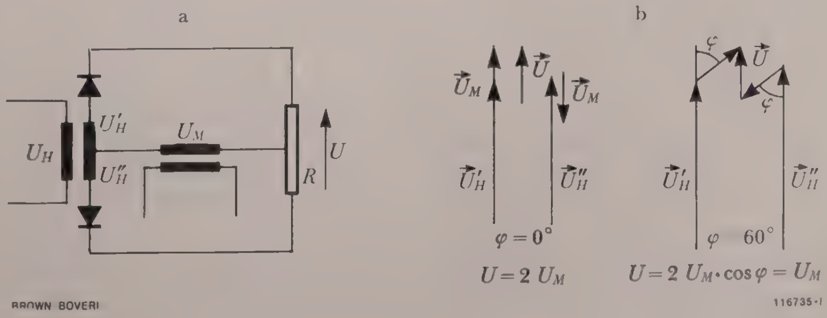


Fig. 4. – Circuit diagram (a) *and vector diagram* (b) *of the single-phase angle measuring system*

U_M = Measured voltage

U_H, U'_H, U''_H = Auxiliary voltages

φ = Phase angle

R = Burden

U = Voltage across R

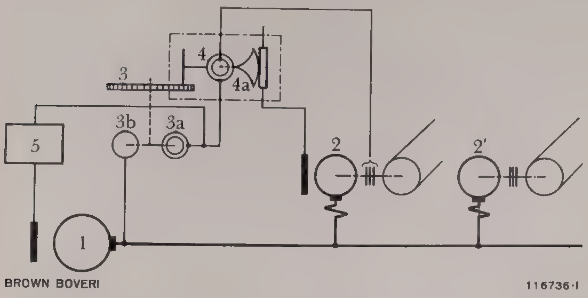


Fig. 5. – Circuit diagram of a busbar-fed sectional drive with centralized draw regulators

1 = Ward-Leonard generator
2, 2′ = Section drive motors
3 = Central draw regulator unit
3a = Master generator (supplying f_0)
3b = Motor driving draw regulator unit
4 = Draw regulator
4a = Sector regulator of 4
5 = Frequency regulator

The equations for small deviations with respect to time from the rated data of the field-controlled motor, represented in the Laplace form with the operator p denoting the differential with respect to time, are given below; the following notation, as used in Fig. 7, being introduced.

For the armature circuit:

Voltage U, current I, torque M, angular frequency ω, moment of inertia Θ, resistance R, inductance L.

For the exciter circuit:

Voltage u, current i, resistance R_e, inductance L_e.

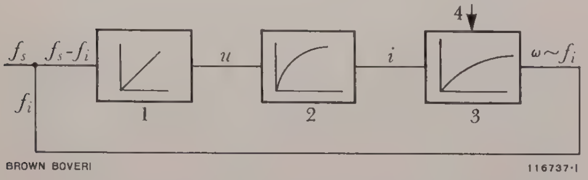


Fig. 6. – Block diagram of the control circuit, showing transfer functions of a drive section

1 = Draw regulator
2 = Motor field
3 = Rotating mass
4 = Load
f_s = Desired frequency
f_i = Actual frequency
i = Excitation current of motor
u = Excitation voltage of motor
ω = Angular velocity of motor

$$U_0 + \Delta U = (I_0 + \Delta I)\,(R + pL) + K\,(i_0 + \Delta i)\,(\omega_0 + \Delta\omega) \quad (1)$$

$$M_0 + \Delta M = K\,(I_0 + \Delta I)\,(i_0 + \Delta i) \quad (2)$$

$$M_0 + \Delta M = \Theta . p . (\omega_0 + \Delta\omega) \quad (3)$$

The dynamic response is now investigated, according to the relationship for small changes in speed, expressed as small changes in the excitation current. The equations for nominal values will therefore not be pursued further.

It would exceed the scope of the present article to obtain detailed derivations. The relationship between $\Delta\omega$ and Δi can easily be found from the above equations (1) to (3).

$$\frac{\Delta\omega}{\Delta i} = -\frac{\left.\frac{d\omega}{di}\right|_{i=i_0} - \left.\frac{dM}{di}\right|_{I=I_0} \cdot \frac{T_m}{\Theta} \cdot (1 + pT_a)}{(1 + pT_a)\,(1 + pT_m)} \quad (4)$$

in which

$T_a = \frac{L}{R}$ = time constant of the armature

$$T_m = \frac{\Theta \cdot R}{\left.\frac{dU}{d\omega}\right|_{i=i_0} \cdot \left.\frac{dM}{dI}\right|_{i=i_0}} =$$

= reduced starting time constant

$\left.\frac{d\omega}{di}\right|_{i=i_0} =$ ratio of speed change to change in field current at the point $i = i_0$

$\left.\frac{dM}{di}\right|_{I=I_0} =$ ratio of torque change to change in field current at the point $I = I_0$

$\left.\frac{dU}{d\omega}\right|_{i=i_0} =$ ratio of voltage change to change in speed at the point $i = i_0$

$\left.\frac{dM}{dI}\right|_{i=i_0} =$ ratio of change in torque to change in armature current at the point $i = i_0$

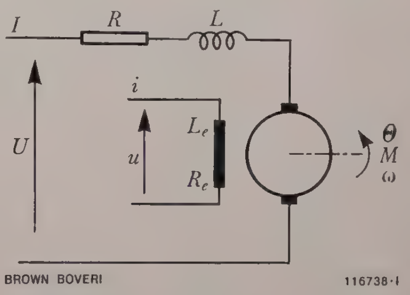


Fig. 7. – Equivalent circuit diagram of the motor

U, I, R, L = Quantities in the armature circuit
u, i, R_e, L_e = Quantities in the exciter circuit
Θ = Moment of inertia
M = Torque
ω = Angular velocity

It is assumed that $T_a \ll T_m$, so that the expression pT_a in the denominator can be neglected compared with pT_m.

For the field circuit we may write

$$\frac{i}{u} = \frac{1}{R_e} \cdot \frac{1}{1 + pT_e} \tag{5}$$

with

$$T_e = \frac{L_e}{R_e} = \text{time constant of the field.}$$

The regulator has a purely integral action, i.e. its speed of adjustment is proportional to the deviation

$$\frac{\Delta u}{\Delta \omega} = \frac{K}{p} \tag{6}$$

By combining the frequency responses of the individual sections and neglecting the time constant T_a of the armature, the total frequency response of the open loop is obtained. Since, as stated earlier, only small deviations from the nominal values occur with field control by a draw regulator, it is possible to simplify equation (4) by neglecting the factor containing the ratio of change in torque to change in field current, namely

$$G(p) = \frac{V_0}{p(1 + pT_e) \cdot (1 + pT_m)} \tag{7}$$

in which V_0 takes all constants into account.

The requirement for a sectional drive to have as uniform a dynamic response as possible and an optimum control speed for all sections can only be fulfilled to a limited extent, because the starting time constants vary by as much as 1:20 and the gain V_0 cannot be made unduly high for stability reasons. By expedient dimensioning of the motors and compensation, an adequate control speed can be attained for the motors at the wet end of the paper machine where, as will be known, the greatest changes in loading occur, and where the paper sheet, although it can withstand the most stretch, must not be overstrained, having regard to its treatment in the subsequent sections.

Each section motor runs up at full field through starting resistors, thereby producing full torque. Shortly before the set working speed is attained, the "service" contactor closes and the draw regulator synchronizes the motor with the desired frequency.

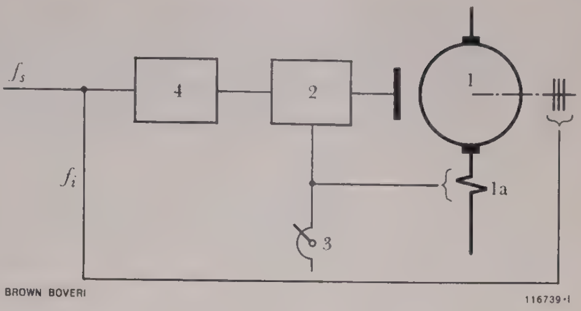


Fig. 8. – Arrangement of the calender control

1 = Drive motor
1a = Interpole winding of motor
2 = Current regulator
3 = For setting desired current
4 = Draw or speed controller
f_s = Desired frequency
f_i = Actual frequency

When the paper has passed the driers it is calendered to obtain a smooth surface. The calender drive differs somewhat from those of the other sections because in this section the paper already has a certain strength. If the drive is controlled to constant stretch, the tension at varying dry content can assume values exceeding the breaking point of the paper. If, on the other hand, the speed control system, which is out of action at no-load, is replaced in service by a current regulator (Fig. 8) the tension in the paper remains constant. This system has given excellent results in numerous installations. The same control problems also occur at the winder, where control is likewise to constant paper tension instead of constant speed (see the article beginning on page 519).

Fig. 9 shows an oscillogram of a speed difference measurement between the third press and the first drier of a newsprint machine with a working speed of 400 m/min, recorded at a speed of 360 m/min.

Speed Control in the Motor Field with Overriding Draw Control

The advantage of a control system with proportional (P) action, i.e. greater control speed, can be neatly combined with that of a system with integral (I) action, when a tacho-generator is coupled to the section motor, generating a voltage proportional to the speed. In a magnetic or electronic controller this voltage is compared with the voltage propor-

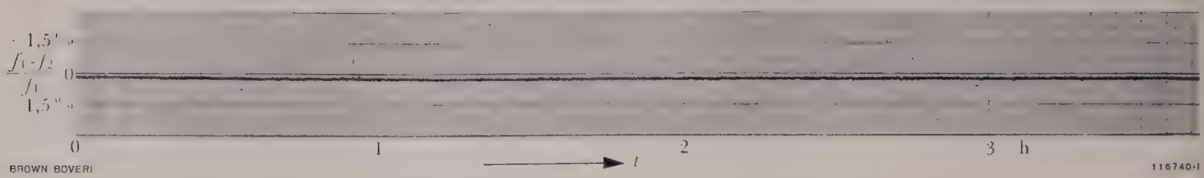


Fig. 9. – Oscillogram of the control system shown in Fig. 5

Measurement of the speed difference between the third press and the first drier as a function of time t, recorded on a paper machine with a top speed of 400 m/min.

f_1 = Frequency corresponding to speed of the third press
f_2 = Frequency corresponding to speed of the first drier

tional to the desired frequency supplied by the draw regulator unit. By means of stabilizing filters and feedbacks it is possible to adapt the response of the controller to the controlled object. As correcting element, and to feed the motor fields, instantaneously controllable thyratrons or robust high-grade magnetic amplifiers with interleaved cores may be employed with advantage (Fig. 10).

The draw or integral controller corrects the desired value of the speed control circuit until the desired and actual values are equal. A speed deviation is rapidly corrected by the speed control circuit, which has a PID action. Residual error and any deviations caused by temperature are eliminated by the draw regulator. The desired stretch, or draw, is set on the draw regulator, whose influence must be at least as great as the necessary range of adjustment.

Reference may be made to Fig. 10 for an explanation of some of the special features of this control system. For the motor we may apply equation (4), but it must be borne in mind that the much higher gain may give rise to over-correction. The non-linearities resulting from the magnetic saturation, and the effect on the field of the armature current must therefore be taken into account in the design. One method of allowing for non-linearities and limitations in the frequency response equation is to use the descriptive function [2]. To deal with this would exceed the scope of the present article though. It is sufficient to establish that the speed and the torque tend towards a maximum limit imposed by the effect of the saturation and the back-e.m.f. on the field. When determining the frequency response, not only the amplitude and phase angle of the sinusoidal input signal must be taken into account, but also the dependency on the amplitude of the input signal. All these requirements must be incorporated in the frequency response equation, including the variable motor time constant T_m (because $\mathrm{d}M/\mathrm{d}I$ varies). Hence

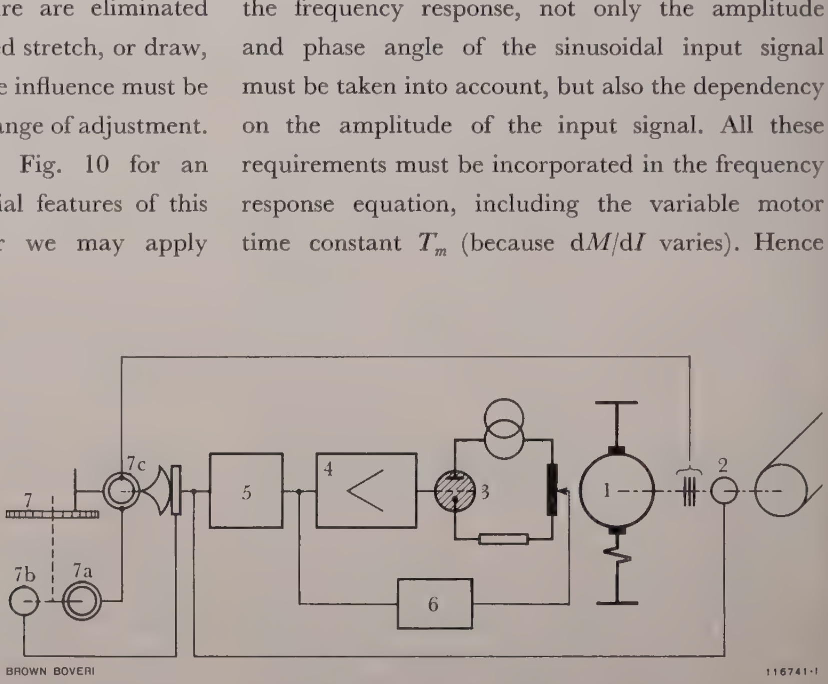


Fig. 10. – Circuit diagram of the electronic control of a drive section with busbar feed

1 = Drive motor
2 = Tacho-generator
3 = Thyratron
4 = Electronic amplifier
5 = Filter
6 = Feedback element
7 = Draw control system
7a = Master generator
7b = Tacho-generator
7c = Draw regulator

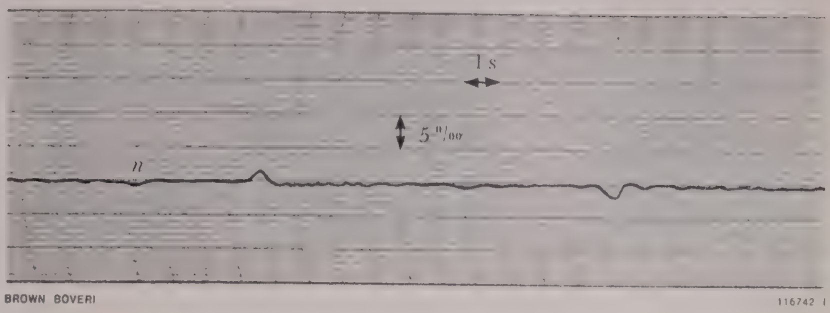


Fig. 11. – Oscillogram of the control system in Fig. 10

Showing the speed *n* during a sudden change in the torque of 10% of the rated figure at rated speed.

to achieve adequate stability for all sections over the entire working range, the speed of control with field control cannot be set to an optimum for all working points.

The requirement that all section drives possess a transfer function similar to a step function change in the input signal, can be realized by suitably dimensioning the feedback elements and filters. Feedback elements which include the non-linear element of the control circuit permit compensation of the non-linear behaviour in such a manner that they partly cancel the weakening of the frequency response over a certain range of frequencies, thereby improving the transient response. By means of calculation, the stabilization measures can be adapted to the constants of each section drive, thus affording a clear picture of the operational response. The oscillogram in Fig. 11, recorded with a simulated drive section (press) on the test-bed, shows the response to sudden changes in load.

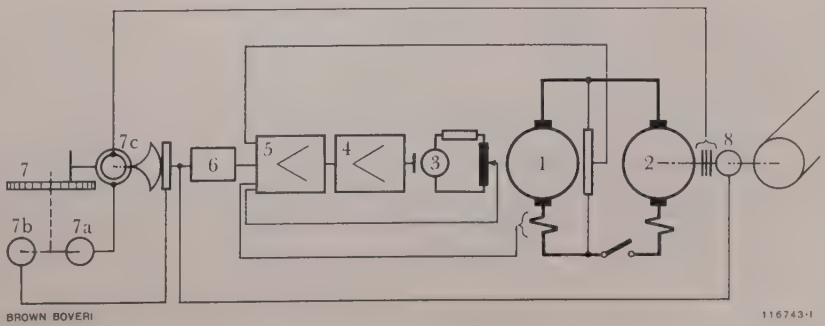
Multi-Generator Sectional Drives

Speed Control with Magnetic Amplifiers and Overriding Draw Control

The advantages of this circuit—independent and thus reactionless operation, the ability to manoeuvre each section separately, short starting and braking times—were fully covered in the article beginning on page 469. Here it is merely proposed to augment those details by a few remarks on the control as such.

Fig. 12 shows the arrangement of the circuitry for a section drive; motors which are, for instance, coupled mechanically or less rigidly to one another by a felt or the wire, are fed from a common generator. As a result, only the advantages of speed (P) control and draw (I) control are combined in this circuit. The inner, i.e. speed control circuit, consists of the magnetic amplifier controller which also takes in the signals for current limitation during

Fig. 12. – Circuit diagram of a drive section with Ward-Leonard generator for each motor, and with magnetic amplifier for speed control with overriding draw control



1 = Ward-Leonard generator
2 = Section motor
3 = Intermediate exciter
4 = Magnetic amplifier correcting element
5 = Magnetic amplifier controller
6 = D action
7 = Draw control system
7a = Master generator
7b = Tacho-generator
7c = Draw regulator
8 = Tacho-generator (actual frequency)

starting, the voltage of the Ward-Leonard generator for emergency stopping, the feedback and differential influences for optimum transient response.

The alternating supply voltage of the magnetic amplifier controller, and the subsequent reset magnetic amplifier, has a frequency of 100 c/s, so that the dead times are only of the order of 5–10 ms. The time constant of the magnetic amplifier controller is of the same order. That of the intermediate exciter can be kept very small by expediently dimensioning the machine. Also the time constant of the field is small, owing to the large power reserve of the exciter. The larger voltage drop, compared with the busbar system, can be reduced by providing compensating windings on the motor and generator of the Ward-Leonard circuit.

A decisive factor for the quality of control is the transfer function of the measuring element; it is essential for there to be good linearity between the speed and the output voltage. Moreover, there must be no temporary changes in the voltage drop between the carbon brushes and the commutator, which would falsify the measurement. Consequently a special type of tacho-generator has to be provided which, besides possessing these properties, must also produce a voltage with as few harmonics as possible.

The partial frequency responses of the Ward-Leonard generator are formed from the equations for the excitation circuit, equation (5), with those for the armature circuit and the motor speed.

From Fig. 7 we may deduce the equations for constant excitation current at the motor:

$$U = I(R + pL) + K_e\omega \qquad (8)$$

$$\Theta p\,\omega = K_t \cdot I \qquad (9)$$

In which

K_e = voltage constant (voltage divided by radians)

K_t = torque constant (torque divided by armature current)

Assuming that T_a is very different to T_m, we obtain the following relationship from equations (8) and (9):

$$\frac{\omega}{U} = \frac{1}{K_e} \cdot \frac{1}{(1 + pT_a)(1 + pT_m)}$$

in which

$T_a = \frac{L}{R}$ = armature time constant

$T_m = \frac{\Theta R}{K_e K_t}$ = reduced starting time constant

U is proportional to the excitation current of the Ward-Leonard generator, provided saturation is temporarily ignored. The relationship between the speed and the excitation current may accordingly be written as

$$\frac{\omega}{i} = \frac{K}{K_e} \cdot \frac{1}{(1 + pT_a)(1 + pT_m)} \qquad (10)$$

This relationship resembles equation (4) for field control, if the factor containing the change in torque relative to the change in field current is zero.

The speed controlled by the inner circuit receives its desired value from the outer loop, i.e. the frequency-measuring circuit. The simplified equation for the frequency response of the opened speed control loop has the following form, in principle:

$$G(p) = V_0 \cdot \frac{(1 + pT_n)(1 + pT_1)(1 + pT_2)}{(1+pT_i)(1+pT_e)(1+pT_{ee})(1+pT_m)(1+pT_a)} \qquad (11)$$

The steady-state gain at zero frequency is expressed by V_0. The integral action time T_i, settling times T_n and the lead times T_1 and T_2 are determined by the feedback and the filter. The time constants of the generator field and the field of the intermediate exciter are denoted by T_e and T_{ee}, respectively. The constants of the magnetic amplifier are small in comparison with the other time constants of the control circuit, and since they do not exert any marked influence on the frequency response, they are not included in its equation.

In the Bode diagram [3] it is possible to assess the dynamic response. It is thus easy to establish how the independent time constants must be selected if they are to satisfy the stability requirements. By means of the relationship

$$\frac{G(p)}{1 + G(p) \cdot H(p)}$$

in which $H(p)$ represents the feedback function, we can express the frequency response of the closed loop. If this is compared with the original behaviour of the system with draw regulator in the motor field, an appreciable improvement will be evident. The adoption of the feedback and the filter is a means of giving the control circuit a PID action. The gain can thereby be appreciably increased and the transient behaviour improved accordingly. Moreover, the requirement that the transfer function have a similar shape for a step function change in all drive sections, can also be fulfilled.

Speed deviations caused by changes in the load on the motor are corrected to within a very small residual error. A 20% change in the rated torque produces a deviation of about 0·04% (Fig. 13a). A change of this order in the speed may be acceptable in the presses, where the paper still possesses considerable elasticity, without the quality being adversely affected (see the article beginning on page 469). Conditions are quite different, however, for the drives at the dry end, where it is preferable for the paper to sag slightly. The smallest sustained deviation would either lead to a loop being formed, which would increase until the paper tore, or the paper would stretch, which is undesirable from the point of view of the quality. To restore absolutely equal speed relationships is the task of the outer control loop. The draw regulator, which is dependent on the angle of rotation, moves out of its position of rest until the actual and desired frequency are equal. A movement of the synchroscope on the draw regulator, however, corresponds to an angular displacement of the spindles of the drive motors. The resultant change in length of the paper sheet between adjacent sections must not exceed a certain figure if loss in production is to be avoided.

While one section drive was starting up, the speed was recorded, together with the voltage and current of the Ward-Leonard generator (Fig. 14). The acceleration and braking current can be set separately for each section, to the benefit of the wire and felts. On the wire, for instance, the starting current is only about half the normal operating current. The speed of the second press of a newsprint machine with a top speed of 750 m/min is shown in Fig. 15 in an oscillogram recorded when the machine was running at 600 m/min.

As with all systems, the calender drive also exhibits some peculiar features. The desired value for speed and draw control is set about 0·1–0·2% higher than the coordinated value. When a narrow strip is threaded through the rolls, a loop is normally produced, which is taken up by temporarily accelerating the motor for a few seconds. When the

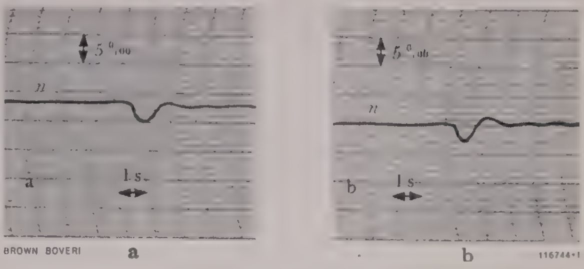


Fig. 13. – Oscillogram of control by the system in Fig. 12

Variation in speed *n* due to a sudden increase in torque of 20% at rated speed, (a) without draw regulator, (b) with draw regulator.

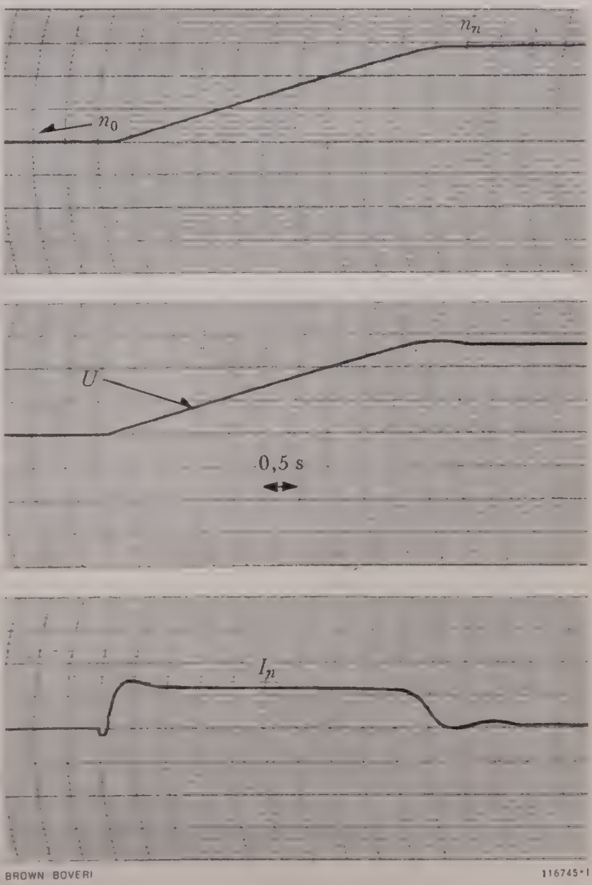


Fig. 14. – Oscillograms recorded during the start of a drive section with the circuitry in Fig. 12

n_0 = Standstill n_n = Rated speed I_n = Rated current
U = Voltage of the Ward-Leonard generator

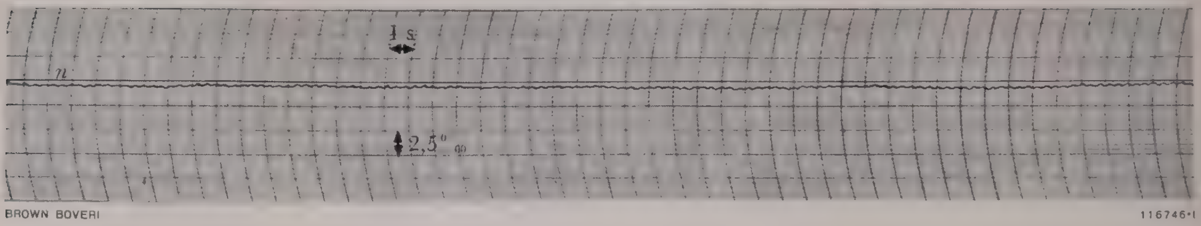


Fig. 15. – Oscillogram of control by the system in Fig. 12

Speed *n* of the second press of a newsprint machine for 750 m/min, recorded at 600 m/min.

strip is wound up tight and passed through the calender in the proper manner, the paper sheet is fed through the rolls at full width, causing the load on the motor to increase, due to the extra work of calendering and the tension. It has been proved that the tension in the paper can be unevenly distributed over the width, due to the sheet drying differently. A change in speed of a few hundredths of a percent can therefore over-strain the paper and lead to wastage. It is therefore an advantage for the speed control circuit to be augmented by an overriding current control circuit, which regulates the load current to a preset value. In a special magnetic amplifier the actual and desired values of the current are compared, and the difference superposed on the speed control circuit. A temporary negative feedback to the magnetic amplifier ensures stable operation. In many cases, on high-speed paper machines, the given desired value of current is corrected by a spring roller, something like a floating roller, immediately before the paper enters the calender. Since the position of this sprung roller is a measure of the paper tension, it is possible to obtain a tension independent of the dryness.

Speed Control with Electronic Amplifiers and Overriding Angular Control

The field of application for electronic control systems has become so widespread in recent years that they are being employed for increasingly severe requirements, including drives in the manufacture of paper. The steady development of electronic equipment and the excellent results which have been gained have succeeded in overcoming the opposition of the paper industry to electronics. The most important advantages are: the high gain, instantaneous control, no reciprocal effect of output on input; also the freedom of the system from losses allows simple components to be used for the stabilization filters, the computation of which is simple, and which are easily incorporated in the control circuit. Additional internal feedbacks effect a certain linearization of the non-linear elements and can easily be combined with the filter. By this means an optimum match can be obtained with the transient response of each section drive. Gas-filled thyratrons are used as correcting element and for feeding the individual generator fields. The advantage of thyratrons is their high gain and their instantaneous control. From experience gained in installations in related industries it is possible to attain a very long life when the tubes are run under the appropriate conditions. In spite of its advantages, the thyratron has not won any great popularity in the paper industry. The prejudice of certain works engineers, that gas-filled tubes are not sufficiently reliable for continuous operation, has still not been overcome.

As a result of incessant development of magnetic amplifiers, particularly due to the employment of interleaved, rectangular cores, which, when incorporated in expedient designs, produce a very small air-gap effect and have a distinct elbow in the hysteresis curve, the magnetic amplifier has become an efficient and extremely reliable correcting element. It is therefore being employed to an increasing extent for feeding the fields of generators. The open-loop control, or adaptation to the controller, is performed by a special intermediate amplifier employing transistors. It is designed to have a two-step action and controls the current in the control winding during the half-cycle in which the core is carrying no current. By this means, fluctuations in the supply voltage and manufacturing tolerances in the transistors are made to exert very little influence. By varying the closing duration of the transistor in the control period the core can be magnetized to different degrees. This shifts the working point on the magnetization characteristic, thereby providing a variable d.c. output.

The combination of magnetic amplifier correcting element and intermediate amplifier is ideally controlled by a transistorized controller. Continuously variable transistorized controllers have already succeeded in establishing themselves for certain applications. Their compactness, immediate readiness for operation and the small amount of attention they need, are their most pronounced advantages. Admittedly they cannot be controlled without a certain dissipation, which explains why the stabilizing networks involve more outlay than with classical tube-type controllers.

The arrangement of the control circuit for each section of the drive is in principle similar to that shown in Fig. 12, with the difference that the magnetic amplifier and intermediate exciter are replaced by the controllers and correcting elements. The current value necessary for limitation during starting and braking each section can no longer be obtained from the interpole winding of the drive motor, because the control circuits and power circuits have to be insulated from one another. For this purpose d.c. transformers are used, operating according to the principle of the current-controlling transductor and providing an unretarded image of the current of the Ward-Leonard generator.

With the controllers and correcting elements described above it is possible to construct extremely responsive control circuits. When an optimum match is obtained, they enable very short correction times to be attained. Furthermore, by suitably setting the filters and feedback it is possible to obtain a frequency response which is similar for all sections of the drive. With these elements the principle of cascaded control circuits is also employed. From inside to outside there are:

the current control circuit (not always in action),

the speed control circuit,

the angle or phase control circuit.

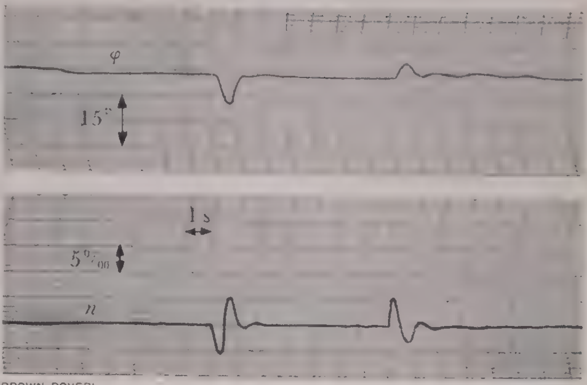


Fig. 16. – Oscillograms of speed control by electronic amplifier with overriding angular control

Speed n and relative rotation φ of the rotor axis in degrees when the torque suddenly changes by 50% of its rated value.

The element which measures the angle, and is designed as a synchroscope, measures the phase difference between the actual and the desired frequencies. Any phase displacement which may occur is transferred mechanically to an induction regulator. A phase discriminator measures the angular rotation of the induction regulator, producing a negative or positive measurand, according to whether the section motor is lagging behind or leading the desired frequency. This measurand, in conjunction with a constant portion depending on the momentary working speed, provides the desired value for the speed control. The arrangement of the outer circuit is thus closed through the speed control circuit.

As already mentioned on page 476, the change in length must be taken into consideration at the dry end of the machine, where the paper usually has a slight sag at the transfer points. A change in load follows a change in speed. The deviation is corrected by the speed control circuit, with the exception of a small residual error. But even when there is a temporary change in speed it is impossible to prevent a phase displacement between the desired and actual frequencies, which produces a change in the length of the paper sheet. It is the duty of the angular measuring element to take up the slack in the paper, by eliminating the change in length. This means it has to restore the conditions prevailing before the disturbance.

Ordinates:
F = Frequency response (to logarithmic scale)
φ = Phase angle between input and output vector in degrees

Abscissae:
ω = Angular velocity to logarithmic scale

Subscripts:
1 = Field control with draw regulator
2 = Multi-generator drive with magnetic amplifier and draw regulator
3 = Multi-generator drive with electronic amplifier and angle measuring element

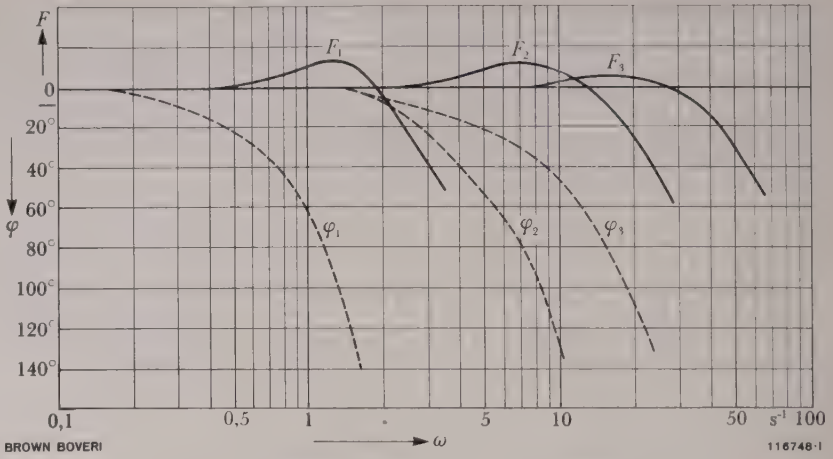


Fig. 17. – Frequency responses of a drive section (press)

For an experimental section drive, simulated on the test-bed and equipped with tube-type controller and thyratrons, Fig. 16 shows an oscillogram of the speed and angle of phase displacement resulting from a sudden change (addition) of the torque, and throwing off 50% of the rated load. By means of the outer angular control circuit the rotor is brought back into its original relative position, which can only be effected by a large temporary increase or reduction in the speed.

Owing to the adaptability of the electronic control units the individual control problem of each drive section can be solved very neatly indeed. The most important commands which have to be executed are:

Switch off
Stop
Inching, forwards and reverse
Auxiliary speed (crawling)
Normal speed

Frequency Response Curve of the Control System

By way of comparison, the frequency response curves of the closed control loops with field control by a draw regulator, for multi-generator drives with magnetic amplifier and draw regulator, and with an electronic controller, are shown in Fig. 17. These curves were determined for a press, but it should be noted that, with the exception of the system of field control with draw regulator, all drive sections exhibit the same response to step-function changes in the desired value, regardless of their different starting time constants.

Conclusions

As this article demonstrates, the conditions in a paper machine impose particularly exacting requirements on the accuracy and reliability of the electric drive and its control system. The close co-operation with the machine builders and paper specialists has enabled Brown Boveri to gain ample experience of the problems of paper-making, and has proved extremely valuable in the development of modern drives. Up to the present the Company has supplied over 240 sets of equipment to paper mills, ranging from very simple drives to complex sectional drives for modern, high-speed newsprint machines with working speeds of up to 750 m/min and wire widths up to 7400 mm. The equipment needed for the modern control systems, as described, with cascaded circuits, is fitted with dependable, thoroughly tested elements, enabling it to fulfil the particularly severe requirements imposed regarding the reliability of sectional drives.

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VARIABLE-SPEED DRIVES FOR WINDERS

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This article deals with the purpose and principle, as well as the control problems encountered on the winder, which follows the paper machine on completion of the paper-making process. For the wide speed range of these machines it is common practice to employ the Ward-Leonard d.c. drive. The energy released during braking the parent reel is absorbed by a braking generator. The resultant methods of control are discussed and the relationship established between the electrical and mechanical quantities, for example in terms of the diameter of the parent reel from which the paper is wound.

Purpose and Principle of the Winder

TO CONVERT the paper produced by the paper machine into a state in which it can be marketed, it has to be cut to a width stipulated by the customers and wound to reels of a definite diameter. These two operations are performed simultaneously on the winder.

It is general practice to allocate a winder to each paper machine. Whereas the paper machine runs continuously, the winder has to be stopped every time a reel is finished, or when tears are repaired. In order that there shall be no serious stoppages in the work of the two machines, their working speeds must bear a definite relationship to one another. Experience has shown that the maximum speed of the winder should be about 2·5 to 3 times that of the paper machine.

It is common knowledge that the working speeds of paper machines have increased enormously in recent years, especially the machine producing newsprint, so that winders have nowadays to be built for top speeds of about 2000 m/min. It is obvious that the requirements for the drive and its control are increased accordingly.

The basic design and principle of the winder will first be explained with the assistance of Fig. 1. The paper is wound off the parent reel 1, passing over various guide rolls 2 and a smoothing bar 3 to the platten roll 4, where it is slit into strips of the desired width by knives 5. The arrangement of the knives and the course followed by the paper vary from one machine supplier to another, but this is of minor importance as regards the drive. The slit paper is then wound on to cardboard cores 7 of the corresponding width. The reel of paper 8 rests on the two wind-up drums 9 and is pressed tight by the rider roll 6. The drive acts on the wind-up drums which rotate the paper reel by friction. The parent reel is braked, creating a definite tension in the paper during the whole process. By keeping this tension constant, not only are tears avoided, but the quality of the paper is greatly enhanced.

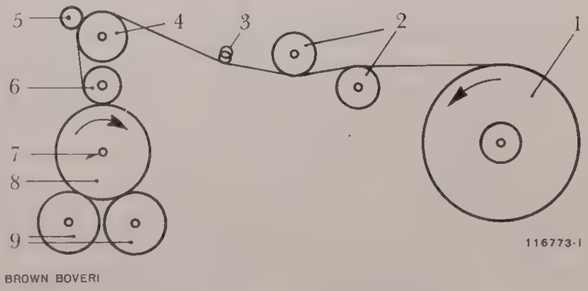

Fig. 1. – Schematic diagram of a winder

1 = Parent reel
2 = Guide rolls
3 = Smoothing bar
4 = Platten roll
5 = Slitting knives
6 = Rider roll
7 = Cardboard core
8 = Finished reel
9 = Wind-up drums

Fundamental Aspects of the Winder Drive

Whereas formerly the winder was usually driven by three-phase shunt commutator motors, the Ward-Leonard d.c. drive has asserted itself almost generally nowadays. The main reason for this is the wide speed range stipulated for high-speed machines, and which amounts to about 1 : 100 in most cases. Whereas the working speeds are ever increasing, the lowest speed stage has remained almost steady at about 20 m/min. This is needed for threading-in the paper, which still has to be performed by hand. In addition to this, the d.c. drive allows regenerative braking to be employed for the pay-off reel. In contrast to older machines, where the pay-off reel was almost always braked mechanically, the present trend is increasingly towards equipping the parent reel with a braking generator, the power produced by which helps to supply the requirements of the wind-up rolls. The energy thus regained is between 30 and 50% of the drive power, according to experience gained. The basic circuit arrangement of the main circuit of the winder drive with regenerative braking is illustrated in Fig. 2.

The torque required by the wind-up drums is practically independent of the speed. Consequently the drive motor only has to have variable armature voltage; its field remains constantly excited. The paper speed is proportional to the speed of the motor, because the wind-up reel is driven at the circumference of the paper reel by friction.

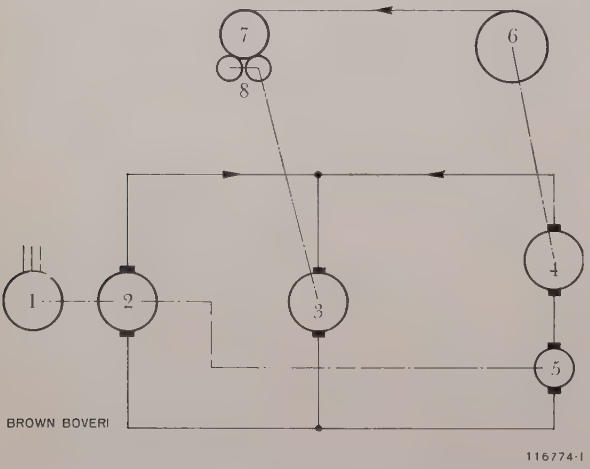

Fig. 2. – Basic circuit of a winder drive with regenerative braking

1 = Converter motor
2 = Ward-Leonard generator
3 = Wind-up motor
4 = Braking generator
5 = Supplementary machine
6 = Parent reel
7 = Finished reel
8 = Wind-up drums

The parent reel is braked centrally through its shaft. In order to attain constant tension in the paper, the braking torque must vary in proportion to the diameter of the reel. Moreover, at constant paper speed, the speed of the drive must be inversely proportional to the diameter of the reel (Fig. 3). These two requirements are simultaneously fulfilled if the field of the braking generator is progressively weakened as the diameter decreases. Fig. 4 shows this relationship with regard to the magnetic flux. The corresponding field current would be somewhat steeper in the upper part of the curve, owing to the saturation. With this pure field control the armature voltage and current of the braking generator are independent of the diameter of the parent reel.

The pulling or braking power P_B may be calculated from two formulae, which can be equated when the losses are ignored:

$$P_B = \frac{F \cdot v}{60.102} = \frac{U_B \cdot I_B}{1000} \qquad (1)$$

in which F = the tension in kg
v = paper speed in m/min
U_B = armature voltage of the braking generator in V
I_B = armature current of the braking generator in A
P_B being expressed in kW.

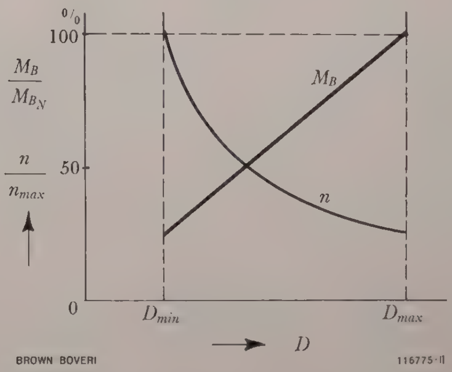

Fig. 3. – Torque M_B and speed n of a pay-off reel as a function of the diameter D of the parent reel at maximum paper tension

$D_{max} : D_{min} = 4$

The suffix N refers to rated value

When the variation of the diameter is only compensated in the field, the speed of the paper is proportional to the armature voltage. From equation (1) it may be deduced that the tension in the paper must be proportional to the armature current. It is thus possible to measure and control the tension in an easy manner.

This method of compensating for changing diameter by merely weakening the field may be employed for diametric ratios D_{max}: D_{min} of 4 : 1 at the most. If field weakening is carried out still further, the machine ceases to run stably. For larger diametric ratios, which are frequently stipulated, the change to combined field and armature control is unavoidable. To vary the armature voltage a supplementary machine has to be used which, for reasons given later, is in the braking generator circuit in any case.

In Fig. 5 the characteristic values are plotted for a diametric ratio of 6 : 1 and constant tension, as a function of the diameter. In this case the distribution is such that the flux of the braking generator varies in the ratio 3 : 1 while the armature voltage varies as 1 : 2, both values being varied simultaneously. In principle the shape of the flux and current curve can be altered to suit requirements. It is merely necessary for the product of the flux Φ_B and the current I_B at each point to correspond to the braking torque M_B required at that point for the particular diameter, and varying with that diameter, as mentioned already

$$M_B \sim \Phi_B \cdot I_B \sim F \cdot D \qquad (2)$$

For the illustration the shape of the two curves was made slightly convex, on account of the control circuit used. From equation (1) the shape of the associated curve for the braking generator voltage can be derived.

For reasons connected with the dimensions, it is convenient for the supplementary machine to be connected in buck-and-boost. When the diameter is large, the supplementary voltage is added (boost) to that of the braking generator, when small it is subtracted (buck). The arithmetical sum of the two voltages corresponds in every case to the voltage of the Ward-Leonard generator.

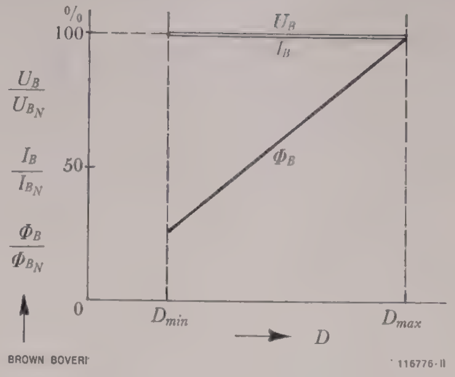

Fig. 4. – Armature voltage U_B, armature current I_B and flux Φ_B of the braking generator as a function of the diameter D of the parent reel for maximum paper tension and speed, with pure field control

D_{max}: $D_{min} = 4$

The suffix N refers to rated value

For the considerations put forward so far the voltage drop in the machines was always ignored. In service at normal working speeds it is insignificant.

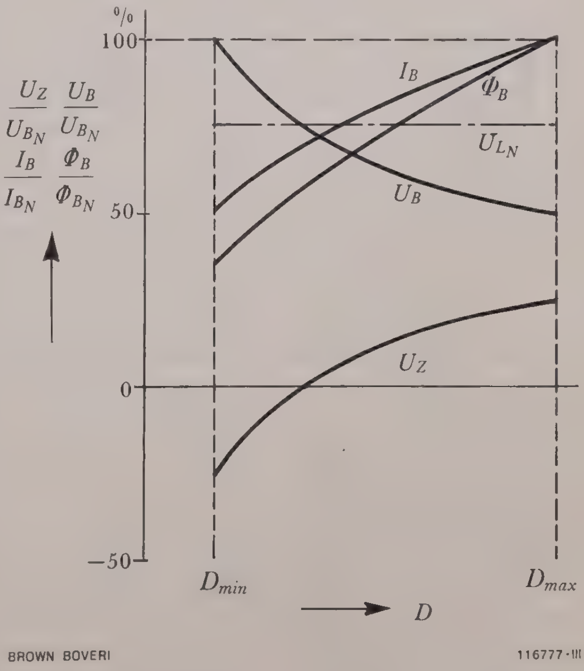

Fig.5. – Armature voltage U_B, armature current I_B, flux Φ_B and supplementary voltage U_Z as a function of the diameter D of the parent reel for maximum paper tension and speed, with combined field and armature control

D_{max}: $D_{min} = 6$

U_L = Voltage of the Ward-Leonard generator

The suffix N refers to rated value

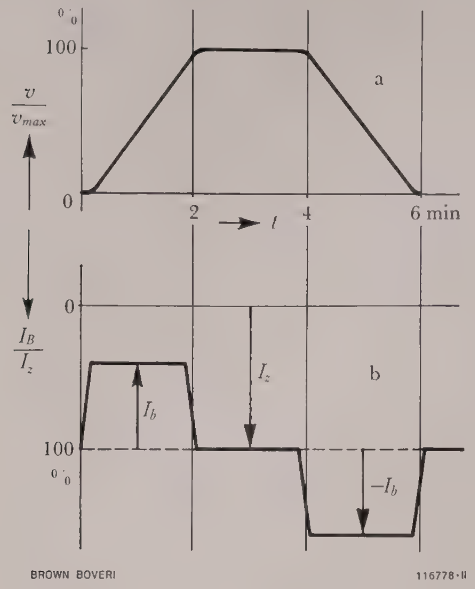

Fig. 6. – Acceleration and retardation of the pay-off reel

Curve a: Speed v as a function of time t

Curve b: Current I_B of the braking generator as a function of time

I_z = Current component for paper tension

I_b = Current component for acceleration

In contrast, it cannot be ignored at the low speeds which are required at the start of every reel when the control of the tension naturally has to function too. Strictly speaking, the speeds of the wind-up motor and braking generator are not proportional to the terminal voltages, but to the e.m.f. induced in the armature. For example, at a threading-in speed of 1%, the voltage drops at the current required amount to a multiple of the e.m.f. The effect of this in practice is that if the voltage drops are not allowed for, the braking generator cannot possibly develop sufficient tension in the paper. It is therefore inevitable that a supplementary voltage should have to be introduced into the circuit, in order to compensate for the voltage drops in the braking generator, and the wind-up motor. Consequently, even with pure field control of the braking generator, it is necessary to include a supplementary machine.

The conditions during acceleration and retardation of the machine must still be considered.[1] Here it must be borne in mind that very large rotating masses are involved with the winder. On the other hand, the acceleration times must not be made too long, in order that the most may be got out of the machine. Hence appreciable torques are required for accelerating and retarding the machine. The acceleration torque needed for the parent reel is then superposed on the braking torque needed to obtain the tension in the paper. In the remarks which follow the torques will be represented by the corresponding currents so that the relationships derived may be adapted to the control system direct.

Since the current of the braking generator would be kept constant by the regulator without special precautions, the pay-off reel would have to be accelerated by the tension in the paper alone, imposing additional stresses which might cause the paper to tear. Conversely, during retardation the paper would be too slack which, from experience, would also cause the paper to tear or severely reduce the quality of the reel. For high-speed winders good compensation of the acceleration is therefore essential. The desired value of the current must be influenced during changes in the speed, in such a manner that the tension remains constant. Fig. 6 illustrates the principle of acceleration compensation graphically. During acceleration the braking generator current has to be reduced by the acceleration component, during retardation increased by the same component. In extreme cases this component may be larger than the tension component, and the generator may have to run as a motor for a short time.

Here the acceleration current is assumed to be constant, but this is only true when the change in diameter is ignored. In fact the acceleration current I_b depends to a large extent on the diameter of the parent reel. It can be calculated from the following equation:

$$I_b = 2{\cdot}74 \cdot 10^{-3} \frac{WD^2\, n^2}{T\, U_B} \qquad (3)$$

in which

WD^2 = the moment of inertia in kgm²

n = the speed in rev/min corresponding to the diameter D

T = time in s to accelerate from 0 to n

U_B = the voltage of the braking generator corresponding to the speed n

I_b = being expressed in A

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[1] The retardation is not dealt with specifically afterwards, because it can be considered as negative acceleration.

The moment of inertia is composed of a constant portion (pay-off reel and any guide rolls driven by the paper) and a variable portion (paper). The latter component is proportional to the difference $D^4 - D^4_{min}$, and therefore increases very rapidly with the diameter of the parent reel D. The formula (3) is generally applicable, including combined field and armature control.

Fig. 7 shows a typical practical example of the curve of the acceleration current in terms of the diameter. It was obtained with a winder for 2000 m/min and a width of 6 m. The weight of the parent reel when full is roughly 9 tons, the moment of inertia about 10 tm². The illustrated curve is seen to have the typical saddle-shaped form of the acceleration current, due to the fact that a decreasing quantity n^2 has to be multiplied by an increasing quantity WD^2.

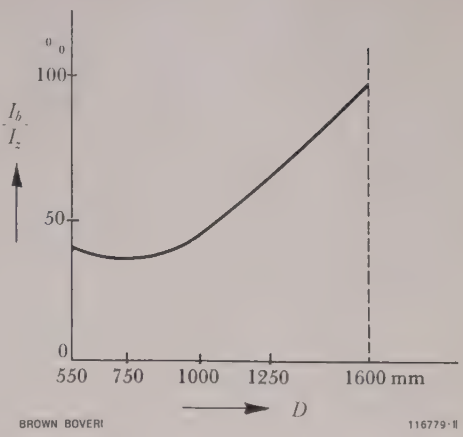

Fig. 7. – Relative acceleration current I_b/I_z as a function of the diameter D of the parent reel

I_b = Acceleration current
I_z = Normal tension current
Paper speed 2000 m/min
Acceleration time 120 s

Control of the Wind-Up Motor

Whereas on older drives the speed was usually controlled by a simple field rheostat driven by a motor, the present trend is for high-speed winders with regenerative braking to be equipped with a system of speed control. The requirements for such a control system are as follows:

The threading-in speed must be maintained during changes in load.

Acceleration and retardation must be linear, but with smooth transitions.

Starting from standstill must not be too abrupt.

Operation must be simple.

Fig. 8 shows the circuit diagram for speed control of the wind-up motor. As a measure of the paper speed, the speed of the wind-up motor is measured by a tacho-generator 4. The voltage of the latter is connected in opposition to a desired-value voltage picked off potentiometer 6, and the difference applied as control quantity to the input of the magnetic amplifier controller 5. This amplifies the input signal and with its output acts on the field winding of the auxiliary exciter 3, which in turn excites the Ward-Leonard generator 1. The auxiliary exciter possesses a second field winding enabling it to overcome remanence and to compensate for the residual current in the magnetic amplifier. The reference

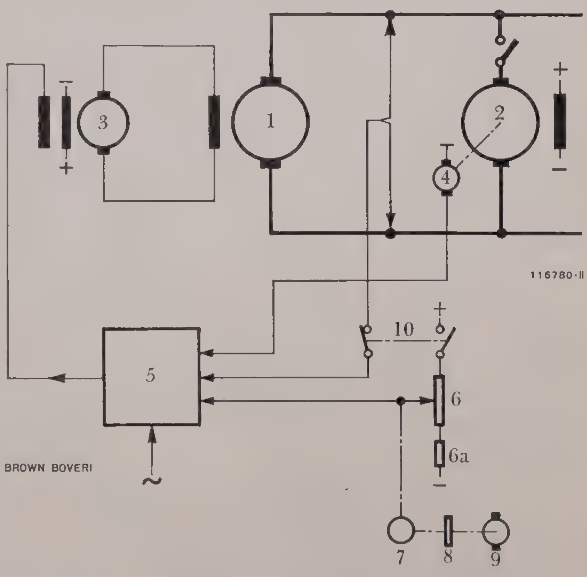

Fig. 8. – Principle of control of the wind-up motor

1 = Ward-Leonard motor
2 = Wind-up motor
3 = Auxiliary exciter
4 = Tacho-generator
5 = Magnetic amplifier controller
6 = Reference potentiometer for working speed
6a = Resistor for desired value of threading-in speed
7 = Servo-motor
8 = Flywheel
9 = Tacho-generator
10 = Changeover contacts for "Stop"/"Running"

potentiometer 6 is driven by the servo-motor 7. The latter is coupled with the flywheel 8 to prolong its starting and run-out times, thus smoothing out the transitions between the steady and transient states of the machine. This is particularly necessary for operational reasons at the start of acceleration. In this way it is also possible for the control of the paper tension not to be rendered unduly difficult at the instant of transition. Coupled to the potentiometer drive there is a small tacho-generator 9 for the acceleration compensation (see below).

At standstill the Ward-Leonard voltage is reduced to zero by the same controller. Only when the machine is switched on does the voltage grow to a value corresponding to the threading-in speed, by which means it ensures that starting is not too abrupt.

The operational sequence is as follows: At standstill the changeover contacts 10 are in the position shown in Fig. 8. The supply to the reference potentiometer is interrupted and the voltage of the Ward-Leonard generator is kept at zero by the regulator. The pick-off of the potentiometer 6 is at the lower end position. When the drive is switched on, contacts 10 change over and the voltage applied to resistor 6a is conveyed to the magnetic amplifier as desired value for the threading-in speed. The magnetic amplifier controls the drive up to the desired speed. If the machine is desired to run at a higher speed, the potentiometer 6 is displaced by its servo-motor on operation of the appropriate rotary switch, the speed of the machine following the potentiometer pick-off rapidly and accurately to the desired value. Normal retardation of the machine follows the reverse sequence.

If the machine has to be braked suddenly, for instance when the paper tears, the reference potentiometer runs quickly back and the machine is braked by regeneration. If the wind-up motor is equipped with a mechanical brake, an additional means of electric braking by regeneration is difficult to adapt, because the mechanical braking effect varies appreciably. In such cases rheostatic braking is preferable. The effect of this is greatest at high speed, where the mechanical brake develops the largest amount of heat and where there is more likelihood of the brake linings being destroyed. For this reason the two braking systems are often made to operate successively.

Control of the Pay-Off Reel

The purpose of controlling the pay-off reel is to keep the tension in the paper constant throughout the entire winding process. For the practical solution of this problem we must differentiate between two cases.

The first, and simpler case is the one in which the diameter of the parent reel varies by not more than 4 : 1, so that pure field control may be employed. In this case the current of the braking generator at steady paper speed is proportional to the tension, and it is sufficient to keep this current constant at the desired value (cf. Fig. 4).

In the second case the diametric ratio is more than 4 : 1 so that a combination of field and armature control must be employed. Here the current is no longer proportional to the tension and control really ought to be to constant power. But this is impracticable because the necessary accuracy is unattainable at the lower speeds. Instead the current is controlled but its desired value is continuously altered as a function of the diameter (see also Fig. 5).

In both cases the most expedient and cheapest method of controlling the current is the well-proved rolling-sector regulator. It offers the great advantage that the dependence of the control resistance on the position of the regulator can be chosen relatively for each single sector. It is thus possible to utilize the various regulator outputs for a wide range of current and voltage characteristics, which is particularly valuable for non-linear compensation. The mechanical regulator, moreover, has the great advantage over other systems in this particular case, in that, for instance if the paper tears, the regulator can be blocked in the position corresponding to the momentary diameter of the parent reel.

a. Pure Field Control

The basic circuit for this kind of control is shown in Fig. 9. In view of its functions, the regulator in this case is shown as a two-sector regulator. Sector I acts on the field winding of the braking generator 3. Sector II is required for the acceleration component. The measuring system compares the voltage drop at the interpoles of the braking generator (actual value of the current) and the voltage of the generator providing the desired value (5). The latter is excited by the reference potentiometer 10. A second field winding is energized by the acceleration compensation circuit. Since the acceleration is linear, owing to the speed control described above, it would be permissible in principle for a constant voltage to be used to feed the compensation circuit, and for this voltage to be left switched on while the speed is being changed. But by this means it is almost impossible for the acceleration influence to coincide exactly with the actual acceleration. The consequence of this would be an appreciable error in tension at the beginning and end of the acceleration process. But, as already stated, since a smooth transition is desired for operational reasons, the drive of the potentiometer for the desired value of the speed is equipped with a flywheel 8, thus creating the ideal conditions for exact compensation of the acceleration. Since, owing to the influence of the speed controller, the machine speed and the pick-off of the potentiometer always correspond to one another with sufficient accuracy, the voltage of the tacho-generator 9 may be considered as a measure of the acceleration and used for feeding the compensation circuit. In order to allow for the dependence of the acceleration current on the diameter of the parent reel, sector II of the regulator is connected in parallel with a fixed resistor in the compensation circuit. This exploits the fact that the position of the regulator always corresponds to the momentary diameter. This simple circuit allows the acceleration effect to be closely adapted to the calculated curve (cf. Fig. 7) when the resistors are suitably dimensioned. The supplementary machine 4 in series with the braking generator should provide a voltage which compensates the voltage drop in the braking generator and approximately that in the wind-up motor. It is therefore excited by the desired-value machine 5.

When the parent reel is full, at the beginning of the winding process, the regulator is in the end position as shown. As the diameter decreases, the pay-off reel is slightly accelerated while the paper speed remains constant. The result of this is that the voltage induced in the braking generator increases, and with it the current. Now the regulator comes into action and weakens the field of the braking generator until the induced voltage, and thus the current has been restored to the desired value. Hence the regulator moves gradually across its full range, and its momentary position always

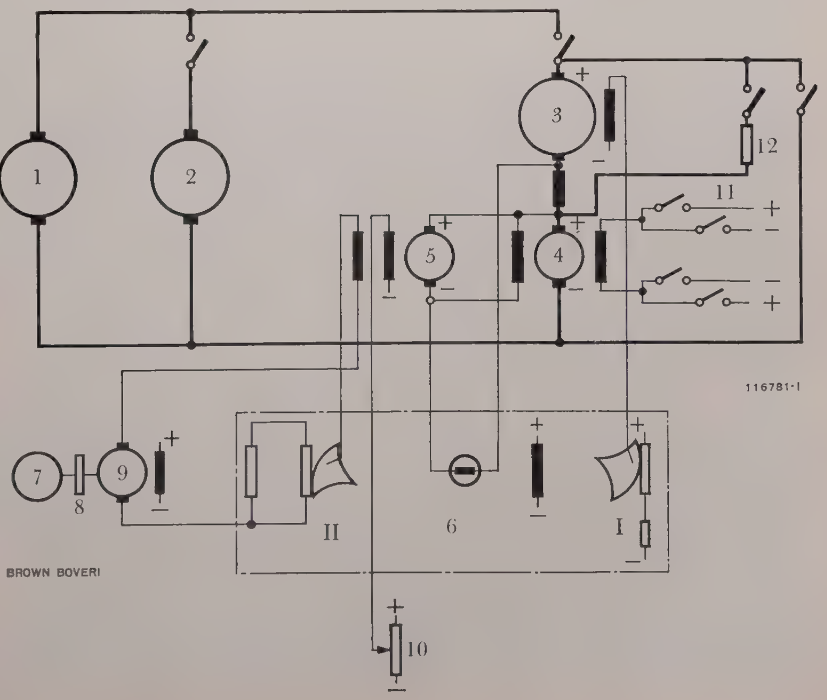

Fig. 9. – Controlling the current of the pay-off reel with pure field control

1 = Ward-Leonard generator
2 = Wind-up motor
3 = Braking generator
4 = Supplementary machine
5 = Desired-value machine
6 = Current regulator, sectors I and II
7 = Servo-motor of speed reference potentiometer
8 = Flywheel
9 = Tacho-generator
10 = Potentiometer for desired paper tension
11 = Control contacts for "Slow forwards–reverse"
12 = Braking resistance

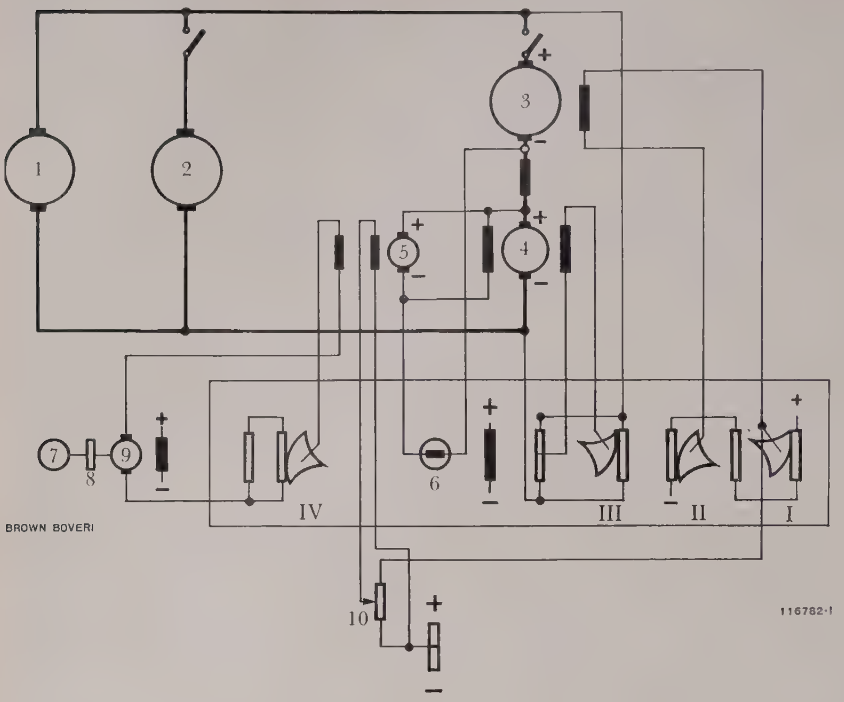

Fig. 10. – Current control of the pay-off reel with combined field and armature control

1 = Ward-Leonard generator
2 = Wind-up motor
3 = Braking generator
4 = Supplementary machine
5 = Desired-value machine
6 = Current regulator, sectors I–IV
7 = Servo-motor of speed reference potentiometer
8 = Flywheel
9 = Tacho-generator
10 = Potentiometer for desired paper tension

corresponds to the diameter of the parent reel. This is also true when the tension is changed on the reference potentiometer, and during acceleration and retardation of the machine, because the corresponding change in current is not effected by changing the field of the braking generator but by the supplementary machine.

During the threading-in process, the work of the machinists is greatly simplified if the heavy parent reel does not have to be rotated by hand. For this task the braking generator and supplementary machine are connected in a separate Ward-Leonard circuit, in which the generator runs as a motor. With the aid of push-button 11 the supplementary machine can be positively or negatively excited, according to whether the parent reel has to run slowly forwards or backwards.

To stop the pay-off reel suddenly there is normally a mechanical brake. To relieve it and to shorten the braking time a system of rheostatic braking is also provided (resistor 12).

b. Combined Field and Armature Control

The circuit diagram of this control system is shown in Fig. 10. On account of the rather complicated nature of the control task, a four-sector regulator is employed in this case. The sectors I and II are connected as a variable voltage divider to feed the field of the braking generator. Sector III is connected as a bridge with a fixed resistance and acts on one of the fields of the supplementary machine 4 to partially compensate for the change in diameter. Since the induced buck-and-boost voltage has to be proportional to the speed, this field circuit is fed with the voltage of the Ward-Leonard generator. The second field circuit of the supplementary machine is used to compensate for the voltage drop, and as under *a* above, is connected to the desired-value machine 5, which is likewise excited from the reference potentiometer 10. Here, though, it must be taken into account that the current of the braking generator for a definite paper tension must vary as a function of the diameter (Fig. 5). To achieve this, the potentiometer 10 is fed from a bridge circuit comprising the two sectors I and II and a fixed voltage divider. In order that this method of compensation may function correctly, the armature and field of the braking generator, as stated before, must follow a similar curve as a function of the diameter, which is quite feasible by suitably graduating the regulator resistances. The second field of the desired-value

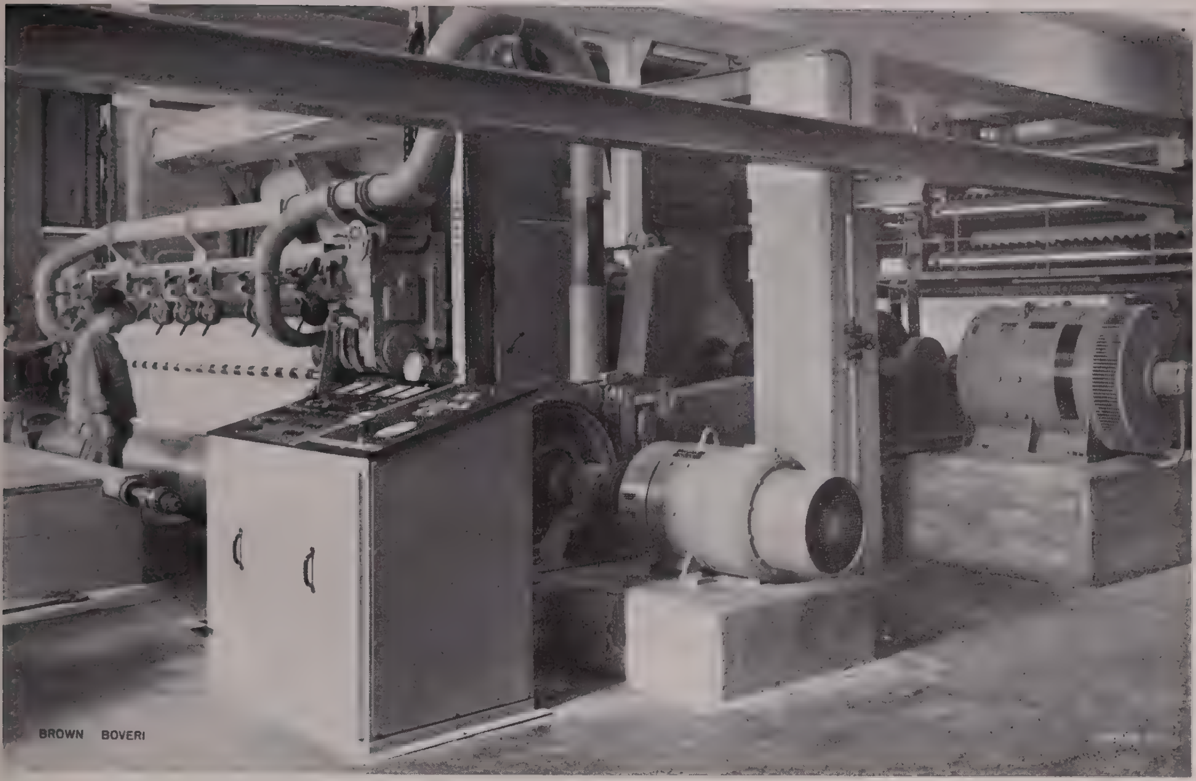

Fig. 11. – Winder with Brown Boveri drive

Maximum speed 1500 m/min Width of paper 4100 mm Diameter of parent reel 1500–410 mm

In the middle of the picture is the wind-up motor, on the right the braking generator. The difference in size of these two machines is related to their speeds. The wind-up drums are driven through gearing with a reduction of 2·16:1. The braking generator is coupled direct with the parent reel and has to be dimensioned for the speed of 320 rev/min corresponding to the maximum diameter. The control desk on the left contains all electrical and hydraulic control and supervisory elements.

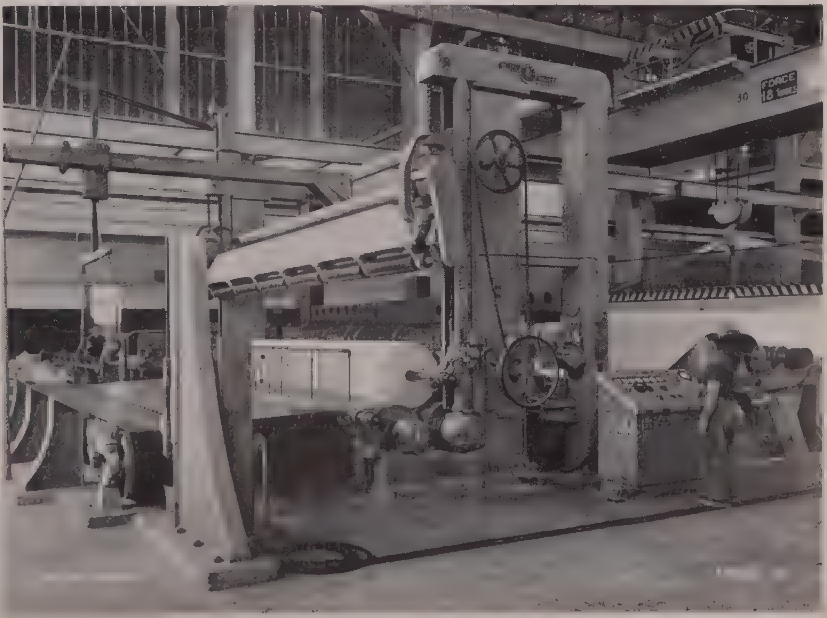

Fig. 12. – Winder for newsprint

Maximum speed 1800 m/min

Width of paper 7000 mm

In this case the wind-up drums are separately driven by 100-h.p. motors. The rider roll and knives are also separately driven.

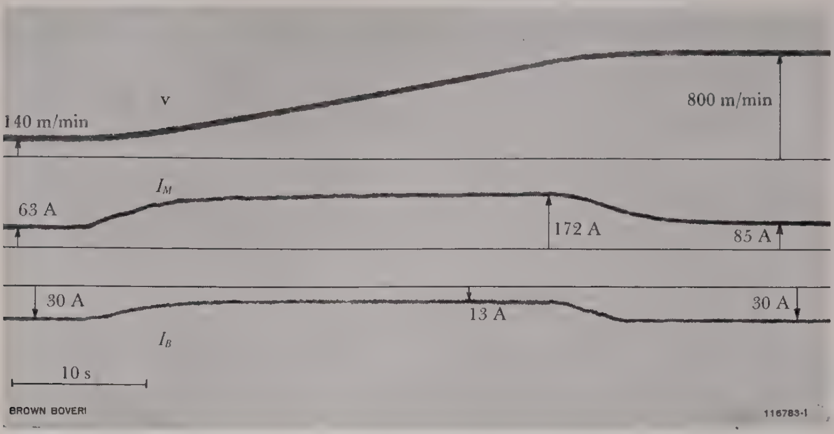

Fig. 13. – Oscillogram of a normal operational acceleration of a modern winder

v = Paper speed
I_M = Current of wind-up motor
I_B = Current of braking generator

machine is for compensating the acceleration in exactly the same manner as in *a*.

Although, at first sight, the control problems with combined armature and field control may appear somewhat complicated, they can be simply solved with the aid of a single four-sector regulator.

Completed Installations and Results

Several modern winders have been equipped with Brown Boveri drives in the last few years, employing the control systems described in the foregoing, or slightly modified versions, all of which have proved extremely successful. Fig. 11 and 12 show views in two such installations.

In the winder shown in Fig. 12 the two wind-up drums, the rider roll and the knives are driven separately. The desired working speed can be preselected by means of a rotary resistor in the control desk. The speed control system is equipped with overriding current limitation, which takes effect during acceleration and braking.

Fig. 13 shows an oscillogram recorded in another plant. It shows the variation with time of the speed, and the currents of the wind-up motor and braking generator during normal operational acceleration. The linearity of the acceleration can be seen to be very good indeed. The transition from the acceleration period to normal speed and vice versa was very smooth, which is very important for the acceleration compensation. Since the moment at which the acceleration influence begins to take effect can never be struck quite accurately, even with appreciable technical outlay, but it can lead to serious error in the tension, care has to be taken to smoothen out the transitions mentioned. The resultant small differences in timing therefore have no effect whatsoever on the tension in the paper.

In conclusion it may be said that Brown Boveri drives for winders, equipped with the control systems described, completely fulfil the operational requirements. Since the paper tension is now completely automatically controlled, operation of the machine has become extremely simple. The regulators used are magnetic amplifiers and rolling-sector regulators, the excellent reliability of which is common knowledge, so that in this respect too the equipment provided has found wide recognition.

(KME) A. DUDLER

ELECTRIC DRIVES OF SUPER-CALENDERS

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The present article first explains the importance of calendering to the paper-making process as a whole. The super-calender is an independent, intermittently operating finishing machine. It is quite common for the paper to reach speeds of 800 m/min in such machines nowadays. The manner in which this machine operates, and the increasing demands on its drive and control are discussed, together with the design and principle of its drive.

Purpose of Calendering
Description of the Super-Calender

NOWADAYS the super-calender is being increasingly incorporated in the paper-making process. A large proportion of printing paper is finished in this machine. The printers make continually more exacting demands as regards the quality of the paper they receive, the most important of which concern the glaze, good printing properties, strength and resistance to humidity.

The process of calendering imparts a polished surface to the paper in a super-calender. Fig. 1 shows the typical arrangement of a 14-roll super-calender, on which both the parent roll and the finished roll are electrically driven. At this point it is advisable to define the term super-calender and point out the difference between it and the ordinary calender. The calender is part of the paper machine proper, whereas the super-calender is a completely separate machine, intermittently employed for finishing. The calender only has steel rollers, while the super-calender has steel and soft rollers, the latter of an elastic fibrous material, such as compressed cotton, bakelized paper or nylon discs.

Fig. 2 shows a 12-roll super-calender. Heavy, rigid frames support the work rolls. The uppermost and the lowest rollers are of steel and larger in diameter than the intermediate rollers. This arrangement is used to ensure that the bottom roller cannot bend under the pressure of the rollers above it. The pressure on the bottom roller in a modern super-calender can easily amount to 100 t or more. In most cases the bottom roller is driven, except for super-calenders for grease-proof paper, in which the third roller from the bottom is usually coupled with the drive.

The demands for higher production and better quality brought about numerous modifications

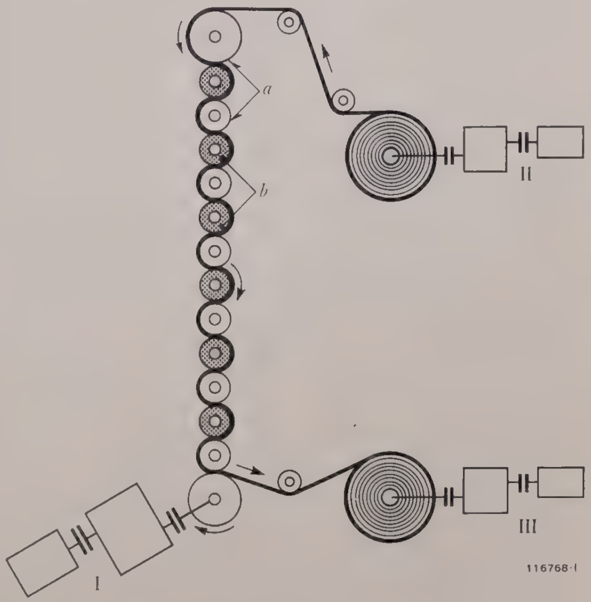

Fig. 1. – Arrangement of a 14-roll super calender with electrically driven pay-off and wind-up reels

a = Steel rolls
b = Soft rolls

I = Main drive
II = Drive of parent reel (braking generator)
III = Drive of wind-up reel (electro-reeler)

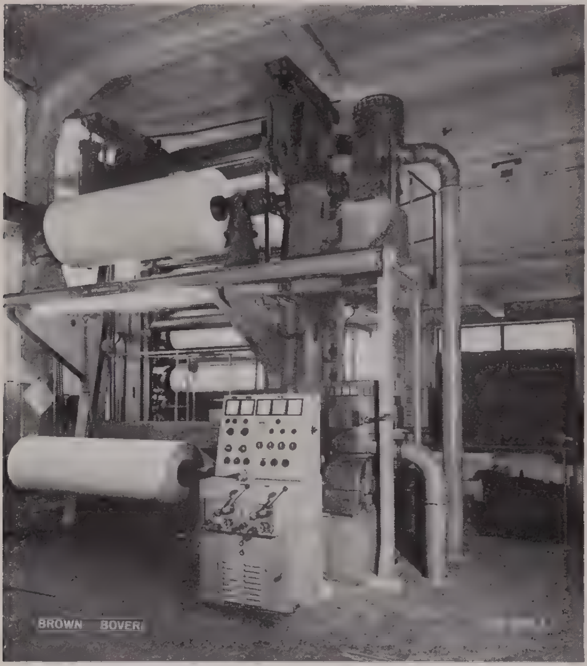

Fig. 2. – Super-calender with twelve rolls, electric wind-up reeler and braking generator

Right rear, the main d.c. motor, rated 320 h.p. at 1650 rev/min. Width of paper 2300 mm, max. working speed 450 m/min. In the foreground is a combined control desk for the electric drive and the hydraulic controls.

in the design of the super-calender. Apart from the previously mentioned heavy frames, the introduction of roller bearings, and the hydraulic loading and unloading of the rollers, has led to a simplification of the control of the machine and has improved the requirements for the drive.

The polish is imparted to the paper in the super-calender by the pressure on the paper between the rolls of different material bringing about a change in structure of the paper. Since the two rolls are in contact under considerable pressure along their full width, the flexible material starts to "flow" in an attempt to regain its original volume. This flowing action produces friction at the surface of the paper, imparting a very smooth finish. The opposite side of the paper, exposed to the steel roll, is given a high polish at the same time. In order to give both sides equal treatment, the succession of steel and soft rolls as shown in Fig. 1 is interrupted by two soft rolls. In order to obtain a perfectly smooth, shiny surface, the paper has to possess a certain amount of moisture, varying from one sort of paper to another.

For driving super-calenders d.c. motors are mostly used, either in the Ward-Leonard circuit, or in a buck-and-boost circuit. This applies not only to the main drive but—on very large super-calenders—for the unwind and wind-up motors too. If the parent reel is braked by a braking generator, some of the drive power can be recovered. The uniform tension, controlled on the unwind and wind-up sides during braking and acceleration exerts a beneficial effect on the quality of the paper. The reels may be drum- or surface-driven by pressure rolls, or centre-driven like the electro-reeler.

Drive Data of Modern Super-Calenders

The working speed and drive power have been considerably increased in recent years. In the last twenty years the working speed has risen from 300–400 m/min to 600–800 m/min, and the specific drive power is now of the order of 120–140 kW per metre width, compared with the figure of 10–20 kW/m which used to be common.

Experience shows that the power required by the super-calender increases proportionally with the reel width, the nip pressure and the weight of the paper, but is more than directly proportional to the increase in speed. Taking the four main parameters into account simultaneously, i.e. the drive power, the working speed, the nip pressure and the weight of the paper, it is possible to arrive at an economic optimum for the drive. Obviously, heavier grades of paper require a much higher torque than the thinner kinds, because they are produced with a much higher nip pressure. On the other hand, thin papers can be produced with a lower nip pressure but then require a much higher working speed. The obvious solution here is to employ a combined system of armature and field control, which is made possible by the favourable operating properties of the d.c. motor.

At the lower end of the motor's speed range, for example with thick paper and a high nip pressure, the motor runs at full field strength, i.e. at low armature voltage and with a high torque. In the region of high speeds, say 80 to 100% of the rated speed, the motor field is weakened at constant armature voltage, the torque increasing roughly in proportion to the speed. This reduction in the torque is admissible because the high speeds are only used for thin papers requiring a low nip pressure.

Principle of the Drives

On super-calenders of low power and speed the finished reel is normally wound up through a gear and slip coupling driven by the main motor, the parent reel being fitted with a mechanical brake. For such conditions a simple Ward-Leonard circuit is quite sufficient, field weakening often being employed for the main motor.

On high-power super-calenders, however, there is usually a separate wind-up motor and a braking generator for the parent reel.

Drives for Small Super-Calenders Without Electric Wind-Up and Pay-Off Drives

The fundamental circuit arrangement for drives of this kind is shown in Fig. 3. This employs a combination of field and armature control, which functions as follows:

The excitation windings of the Ward-Leonard generator 1 and the main motor 2 are interconnected in such a way that the generator is only excited by the small auxiliary exciter 3. For the excitation of the motor the voltage of the auxiliary exciter is connected in opposition to the fixed basic excitation voltage. When the excitation current from 3 increases, influenced by the variable resistor 4, the voltage of the Ward-Leonard generator increases, while the motor excitation steadily decreases. In this manner a close approximation is obtained to the requirements listed above under the heading "Drive Data of Modern Super-Calenders". It is, however, essential for the machines to be sufficiently saturated in operation. Another important advantage of this circuit is that only one quantity has to be varied, thus simplifying the task of the operator. With a suitable setting it is possible to obtain a reasonably linear relationship between the excitation current as reference input and the speed. The variable resistor 4 is driven by a servo-motor, controlled by a switch or push-button from the control desk. The relationship between the speed, the voltage of the Ward-Leonard generator, the motor field and the excitation current of 3 is plotted in Fig. 4.

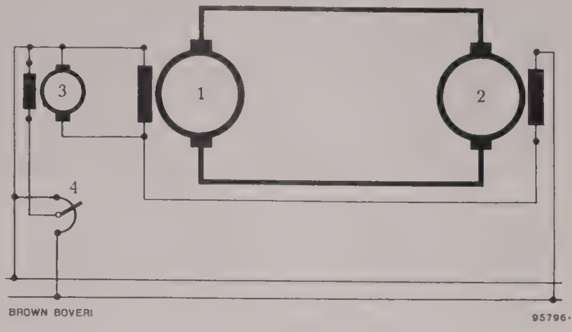

Fig. 3. – Circuit diagram of a simple super-calender drive with combined armature-field control

1 = Ward-Leonard generator
2 = Drive motor
3 = Auxiliary exciter
4 = Variable resistor for setting the speed of the calender

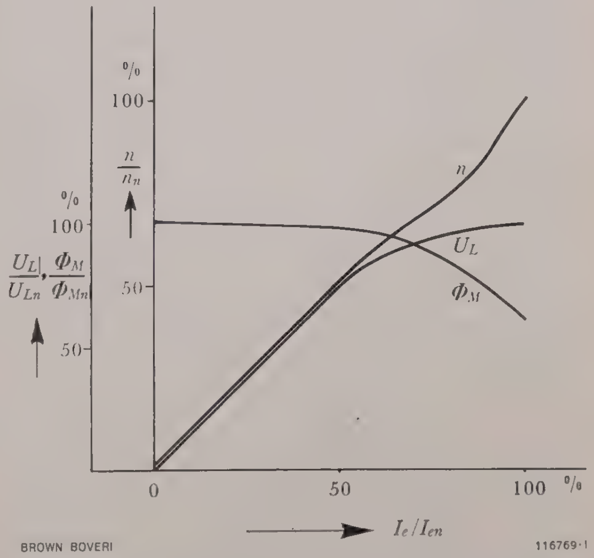

Fig. 4. – Characteristics of a super-calender with combined armature-field control

U_L = Voltage of Ward-Leonard generator
Φ_M = Magnetic flux of motor
I_e = Excitation current of motor
n = Speed of motor

100% represents the respective value under rated conditions (denoted by subscript n). At high speeds the voltage of the Ward-Leonard generator increases only slightly, while the motor field is increasingly weakened.

Drives for Large Super-Calenders With Electrically Driven Parent and Wind-Up Reels

Main Drive

The higher the working speed of the super-calender is made, the more important it is for it to function perfectly. The following main requirements must then be observed:

1. The paper must be threaded in at constant speed, regardless of the quality of the paper and the nip pressure.
2. The working speed must be kept constant.
3. Acceleration and deceleration must be uniform and powerful, so that the machine can run at its full working speed as long as possible.
4. Emergency braking in the event of the paper tearing must be very rapid indeed, the braking current being limited to a definite value.

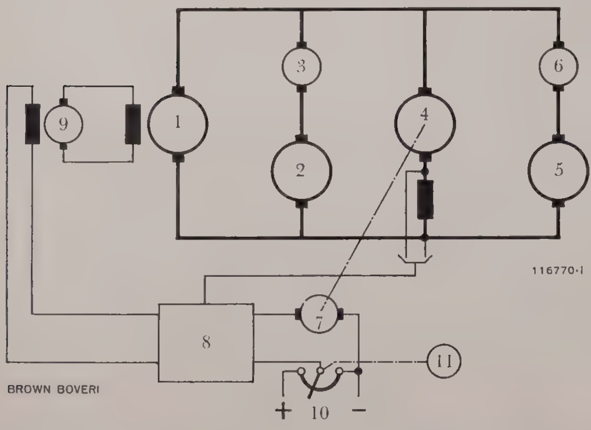

Fig. 5. – Circuit diagram of a super-calender drive controlled by a magnetic amplifier

1 = Ward-Leonard generator
2 = Wind-up motor
3 = Booster
4 = Main motor
5 = Braking generator
6 = Booster
7 = Tacho-generator
8 = Magnetic amplifier
9 = Auxiliary exciter
10 = Variable resistor (for setting desired value)
11 = Motor driving variable resistor

A full diagram for pay-off reels with braking generator is to be found in Fig. 9 on page 507.

These requirements are easily fulfilled by controlling the drive with magnetic amplifiers. Fig. 5 shows the relevant block diagram. The main motor 4 runs direct off the voltage of the Ward-Leonard generator. Supplementary machines 3 and 6 must be connected in series with the braking generator 5 and the wind-up motor 2, respectively. The paper speed is, of course, controlled by the main motor, which in this case operates without field weakening. The tacho-generator 7 coupled to the main motor provides a voltage proportional to the speed. This is compared with a desired-value voltage, provided by a motor-driven variable resistor 10, via one winding of the magnetic amplifier 8. The latter, which is driven by the difference between the desired and actual value, acts upon the exciter 9, which in turn excites the generator 1.

Provided the gain is sufficiently high, the system of speed control ensures that the speed for threading-in the paper is very low compared with the working speed (of the order of 1–2%), and that the speed of the motor exactly follows the given desired value. If the latter is subject to linear variation with respect to time, the desired uniform acceleration or retardation of the paper is obtained. As soon as the Ward-Leonard circuit is opened, a magnetic amplifier is allowed to act upon the generator voltage in such a manner that it is reduced to zero (not shown in the diagram). In this way it is possible to ensure perfectly smooth starting. If the machine has to be braked suddenly in an emergency, the reference potentiometer setting the desired value runs back at an accelerated rate and the machine is braked by regeneration, i.e. the main motor runs as a generator, the braking current being restricted to the permissible value by the magnetic amplifier.

Fig. 6 and 7 show oscillograms recorded on super-calenders with controlled Brown Boveri drive. As may be seen in Fig. 6 both the acceleration and braking are linear. Fig. 7 shows the effect on the various quantities during emergency braking. The motor current exhibits the desired, almost rectangular shape.

Parent reel

On high-speed super-calenders the parent reel is equipped with a braking generator instead of with

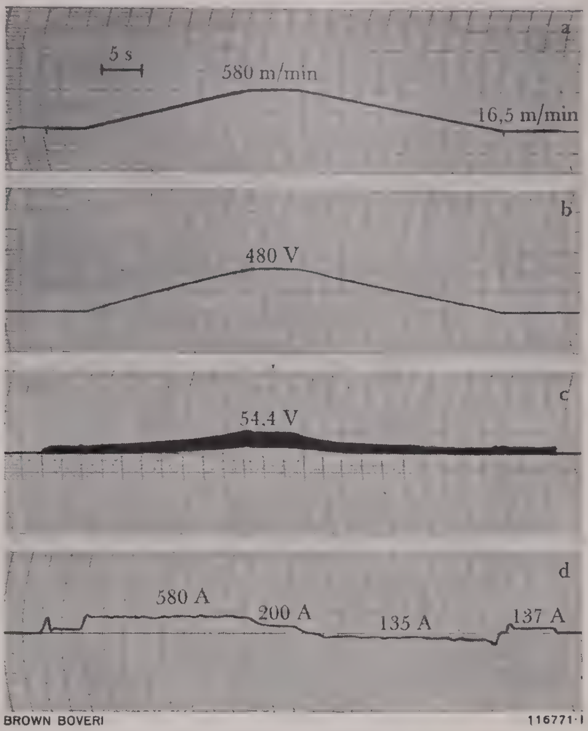

Fig. 6. – Oscillograms recorded on a super-calender with Ward-Leonard drive and magnetic amplifier control

Starting and normal braking at no-load

a: Paper speed in m/min
b: Voltage of Ward-Leonard generator
c: Voltage in field of auxiliary exciter 9 in Fig. 5
d: Motor current

a mechanical brake. The function of the braking generator is fully described in the article beginning on page 501, together with the task of the booster and the principles of control. Here only the main advantages of the braking generator will be briefly underlined:

1. The tension in the paper is regulated at the desired value, the current of the braking generator being kept at a desired value set by hand.
2. During acceleration and retardation, the desired value of the current of the braking generator is automatically corrected by a suitable dosed signal (acceleration compensation) in such a way that the desired tension is maintained. This correction is naturally governed by the diameter of the parent reel and thus by its inertia. The acceleration of the paper may be so powerful that the braking generator has to act momentarily as a motor. On pay-off reels fitted with a mechanical brake, the roll is accelerated by the tension of the paper. The rate of acceleration, or the acceleration period, is limited according to the resistance of the paper to tearing. This limitation can be dispensed with, as stated already, when a braking generator is used, because the tension component, which exceeds the normal tension in the paper, can be produced by running the braking generator as a motor.

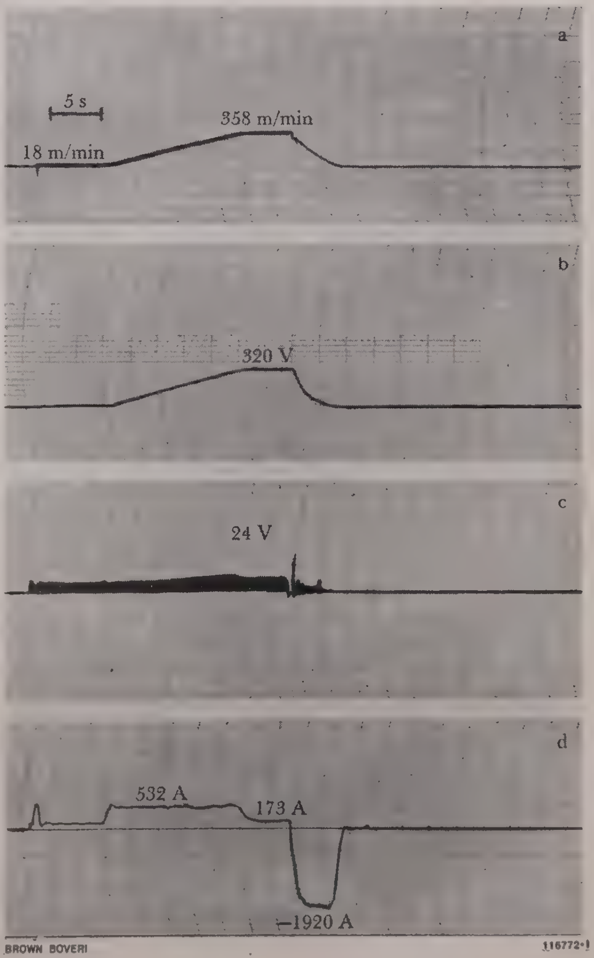

Fig. 7. – Oscillograms recorded on a super-calender with Ward-Leonard drive and magnetic amplifier control

Starting and emergency braking at no-load.
a, b, c, d: as for Fig. 6

Reel drives

The reel of finished paper is normally driven by friction by one or two rider rolls. The rider may itself be driven by the main motor through gearing and a slip coupling, or be coupled to a separate motor. In the latter case the wind-up motor is supplied by the Ward-Leonard generator, assisted by a booster. The field of the wind-up motor thus remains constantly excited, while that of the booster is excited through a rolling-sector regulator, the rotary system of which compares the set winding current with the actual value in the wind-up motor. In this case it is not possible to compensate the acceleration exactly, because there is no quantity available to indicate the diameter of the reel, unless of course a special device is provided to pick off the diameter. On account of the high inertia of the rider roll, that of the paper reel does not exert such an important influence, so that the desired value of the winding current can be corrected by a fixed amount during acceleration or retardation.

Electro-reeler

Fine and special papers, which have to be wound up lightly, must be wound by a centre-driven electro-reeler. This, like the braking generator, ensures that the tension in the paper is constant under all service conditions. In this case too the wind-up motor is connected to the Ward-Leonard generator assisted by a booster. The control of the winding current is also the task of a rolling-sector regulator acting on the field of the wind-up motor. The relationship between the diameter of the reel, the winding current and the speed are fundamentally the same as for the braking generator. The sole difference is that the winding process starts with a small diameter, the motor field changing gradually from the weakened state to full strength. Attention may be drawn at this point to the article on the winder (see page 501). As in that machine, the booster is utilized in the present case for partial compensation for the large diametric ratio of, for example, 1:4. The position of the winding current regulator is then a measure of the reel diameter, so that compensation of the acceleration, which is far more important on the electro-reeler than on the reeler with rider rolls, can be effected exactly.

Operation of the Super-Calender

The controls and supervisory devices for the electric drive are combined with those for the machine and the auxiliaries on a joint control desk (Fig. 2). In spite of the widely varied nature of the tasks which a super-calender has to perform, it is an easy machine to operate. Above all, on machines equipped with a braking generator, there is no longer any need to continually readjust the brakes.

At the start of the process the paper has to be threaded in the machine. For this, on receipt of a special command for the pay-off reel to move slowly forwards, the braking generator with booster is connected with a separate Ward-Leonard circuit and driven as a motor. When the paper has been started on the wind-up reel, the braking generator runs slowly in the opposite direction to stretch the paper, an appropriate command having previously been given. Before commencing the process of calendering proper, the tension in the paper on the pay-off and wind-up sides has to be set by means of a pair of potentiometers. Hence, immediately the machine has been switched on, effected by the command for "crawling", the paper has the desired tension. The appropriate working speed can then be adjusted by a lever switch for "slower"–"faster". Acceleration and retardation then commence smoothly.

With modern super-calender drives work is rationalized and operation simplified, which of course is reflected in the quality of the paper.

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REEL DRIVES ON PAPER MACHINES

676.2.053.62–83

This article describes the mechanical drive of the reel which winds up the finished paper at the end of the paper machine, comparing the main advantages of the electro-reeler and what may be termed the universal-drive reel, and explaining each in detail. The author also deals with the associated problems of control.

Requirements

WHEN designing the drive for a reel, one condition which must always be taken into account is that the tension in the paper must be kept constant at a figure variable in the range 1:6. Moreover, the tension for a particular sort of paper must be maintained at one definite setting all the time. In certain special cases the stipulation is made that the tension should decrease with increasing radius of the reel, to prevent the inner layers of paper from being too tightly compressed.

The Mechanically Centre-Driven Reel

The paper reel which has to be wound up in this case is driven at the centre through a friction clutch. When the paper speed is constant and constant paper tension is stipulated, the torque increases in proportion to the growing diameter of the paper reel, whereas the speed must decrease in inverse proportion to the dimater. By gradually tightening the clutch the torque is increased with growing diameter in such a manner that the stipulated tension is maintained. Thus the fulfilment of this requirement depends on the skill and experience of the machine operator, being rendered more difficult by wear of the friction surfaces, as well as by the effects of temperature and lubrication oil. The eventual outcome is badly wound reels of paper. Furthermore, when the paper tears, the clutch must be released at once to prevent the reel from suddenly speeding up.

Disregarding the difficulties listed above, which can be eliminated by a mechanical speed governor, the conversion of the slip energy into heat by the clutch represents an appreciable loss of power, as will be clear from the following:

With constant paper speed and tension, the useful power imparted to the reel during winding remains constant (see also page 519). Consequently the power applied to the driving half of the clutch at constant speed must increase proportionally with the growing diameter, as shown by equation (1)

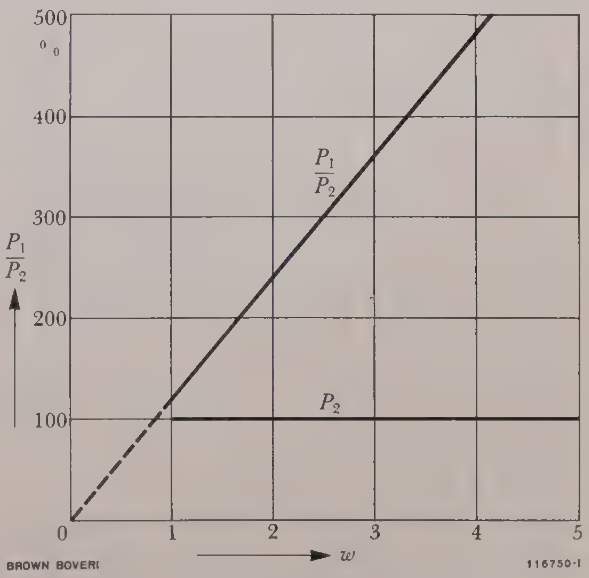


Fig. 1. – Power diagram of the reel drive

P_1 = Applied power

P_2 = Useful power

w = Diametric ratio (d_{max}: d_{min}) of full to empty reel

$$P = \frac{n\,M}{716} = \frac{n\,d\,F}{2 \times 716} \qquad (1)$$

where M = torque in kgm

P = input power in metric h.p.

n = constant speed of driving shaft

F = constant tension in paper in kg

d = varying diameter of reel in m

With a ratio of 4:1 between the diameters of the full and empty reels and with a lead of 20% by the winding reel, the applied power will be 4·8 times the useful power. Hence about 79% of the input power is converted into heat when the reel is full.

The Surface-Driven Reel

On this kind of machine, also known as the pope-type reel, the paper is driven by peripheral friction between the actual reel of paper, supported by a pivoted forked arm, and the wind-up drum. The drum is driven either off the main transmission shaft, or by a d.c. motor supplied by the Ward-Leonard generator of the paper machine which, for particularly strong papers, needs a system of current control to keep the tension constant on the one hand, and to protect the motor from overload on the other. The ease with which the paper is wound on, up to the highest paper speeds, is the outstanding advantage of the surface-driven reel. But the quality of the reel can be adversely affected if the paper is allowed to press against the drum with its full weight, which of course increases with its diameter. To ensure constant pressure the forked arm of the wind-up drum is pivoted down into the horizontal position, in which the pressure can easily be adjusted hydraulically or pneumatically, independent of the weight of the reel, and then does not need to be changed. The universal-drive reel to be described later is an advanced version of this system. Fig. 2 shows the schematic arrangement of the surface-driven reel.

The Electro-Reeler

This represents the ideal combination of the centre-driven reel and the individual drive controlled to constant paper tension, and is widely employed for paper speeds up to about 150–200 m/min. The advantages of this drive system are that it completely eliminates the drawbacks of the mechanically

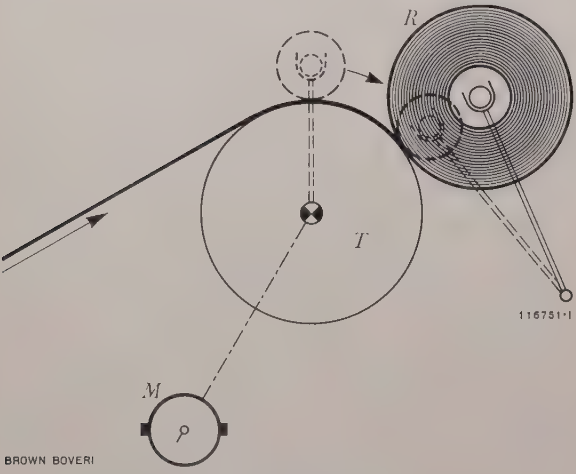


Fig. 2. – Schematic sketch of the surface-driven reel

M = Motor driving the wind-up drum
T = Wind-up drum
R = Reel of paper

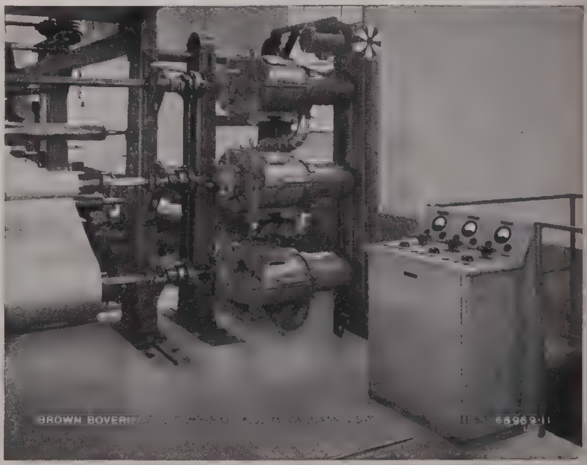


Fig. 3. – Electro-reelers of a paper machine with a sectional drive for a wide speed range

All the instruments and controls necessary for operation and supervision of the three reels are accommodated in the desk. By means of changeover gearing it is possible to wind the paper on to rods, drums or collapsible reels.

centre-driven reel mentioned previously. The ease with which it is controlled moreover assures maximum reliability and allows the paper to be wound on without surges and losses. The paper is transferred from a full reel to an empty shell at an exactly preset speed, the lead of the empty shell being set once and for all for a particular sort of paper by a potentiometer, the corresponding value being marked on an indicator.

Fundamental Conditions During Winding

At constant tension the torque, measured at the journal of the wind-up drum, increases in proportion to the growing diameter of the reel.

$$M = F\frac{d}{2} \qquad (2)$$

where M = torque of the driven shaft
F = tangential force (paper tension) on the reel
d = varying diameter of the reel

Furthermore, if d_0 denotes the diameter of the wind-up drum, the diametric ratio w is given by

$$w = d/d_0 \qquad (3)$$

The working speed determined by the paper machine dictates the speed at which the electro-reeler must run, i.e.

$$n = \frac{v}{\pi d} \qquad (4)$$

where v denotes the paper speed.

From equation (4) it may be seen that the motor speed is inversely proportional to the diameter of the reel, i.e. it varies with respect to time according to a symmetrical hyperbola when v remains constant. Hence for the power

$$P = Fv \qquad (5)$$

or $Fv/(60 \times 75)$ metric h.p. when F is in kg and v in m/s.

For a definite paper machine speed, therefore, the power remains constant if the tension does not change. The wind-up motor must consequently be controlled to constant power.

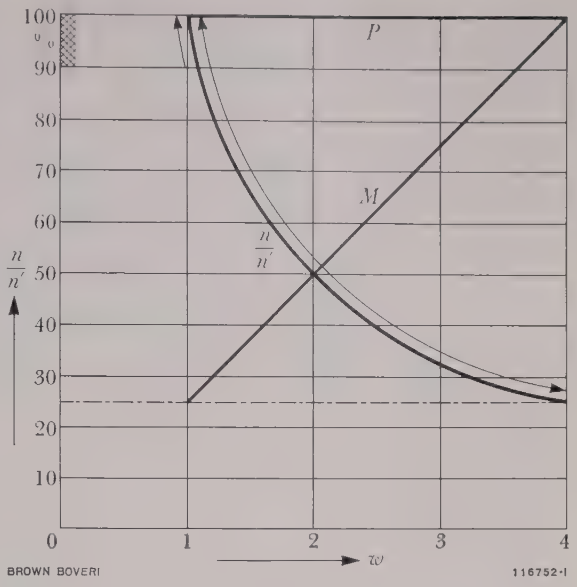


Fig. 4. – Mechanical data of the electro-reeler (or universal-drive reel) in terms of the diametric ratio

P = Power
M = Torque
n = Speed of the wound reel
n' = Speed of the empty reel
w = Diametric ratio (full: empty reel)

The cross-hatched area between 90 and 100% on the ordinates is the changeover region for the universal-drive reel.

Tension Control

In Fig. 5 the wind-up motor is fed from the Ward-Leonard generator of a sectional drive in such a manner that the basic speed corresponds to the generator voltage on the one hand, while the paper tension and load current of the wind-up motor are proportional to one another on the other. When pure field variation is employed this implies constant armature current with increasing torque in the ideal case. In installations provided by Brown Boveri the losses varying with the speed and diameter are automatically corrected during the entire winding process by means of a booster. It should be pointed out that, for particularly fine paper, the losses can amount to a multiple of the effective pulling power and must be compensated for at all costs if the tension has to be kept constant. If the diametric ratio also involves exceeding the range of field control, the voltage of the Ward-Leonard generator is

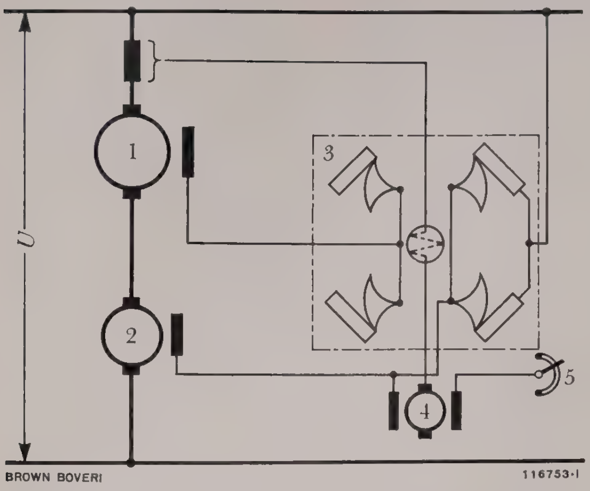


Fig. 5. – Basic circuit of the electro-reeler (or universal-drive reel) fed by the Ward-Leonard generator of the paper-machine drive

U = Ward-Leonard voltage
1 = Wind-up motor
2 = Negative booster
3 = Reel regulator with four rolling sectors
4 = Desired-value machine
5 = Potentiometer for setting tension

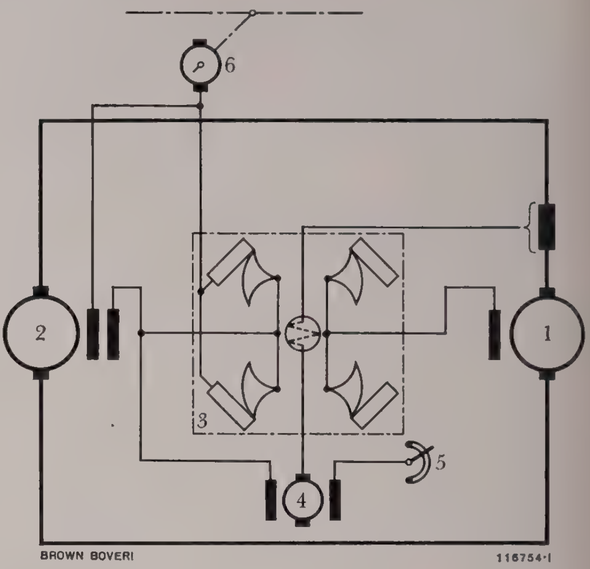


Fig. 6. – Circuit of the electro-reeler (or universal-drive reel) fed by a separate Ward-Leonard generator

1 = Wind-up motor
2 = Ward-Leonard generator
3 = Reel regulator as in Fig. 5
4 = Desired-value machine
5 = Potentiometer for setting tension
6 = Reference machine, driven by the paper machine

reduced accordingly by negative boost, and the control range widened. The quick-acting regulator shown connected as a current regulator in Fig. 5 influences the fields of the wind-up motor and the booster simultaneously, as well as an auxiliary winding of the desired-value machine, in order to fulfil the stipulated conditions.

The readjustment of the desired value necessitated by the reduction of the Ward-Leonard voltage is thus effected automatically by the reel regulator which ensures that a value is provided corresponding to every diameter. By shifting the regulator segments for the booster and desired-value machine in accordance with the Ward-Leonard voltage, the power is made to match the speed of the paper machine. A latching device prevents the regulator running back when the paper tears, so that the reel is not accelerated to a dangerous speed, and at the same time ensuring that the lead set on the regulator, and necessary for taking up slack, is maintained. The end of the winding process is signalled to the machinist by a lamp.

The circuit of an electro-reeler and of a universal-drive reel using a separate Ward-Leonard generator for the wind-up motor, with a longitudinal transmission on the paper machine, is shown in Fig. 6. The Ward-Leonard voltage is reduced by changing the generator field direct.

The Universal-Drive Reel

As already stated under the heading of surface-driven reels, this type of reel is a combination of the well-known pope-type reel and the electro-reeler. As shown in Fig. 7, it is situated at the end of the paper machine.

Principle

According to the requirements for the pope-type reel, the paper is wound on to the shell pressing on to the wind-up drum and wound up by the friction between the drum and the paper. When the

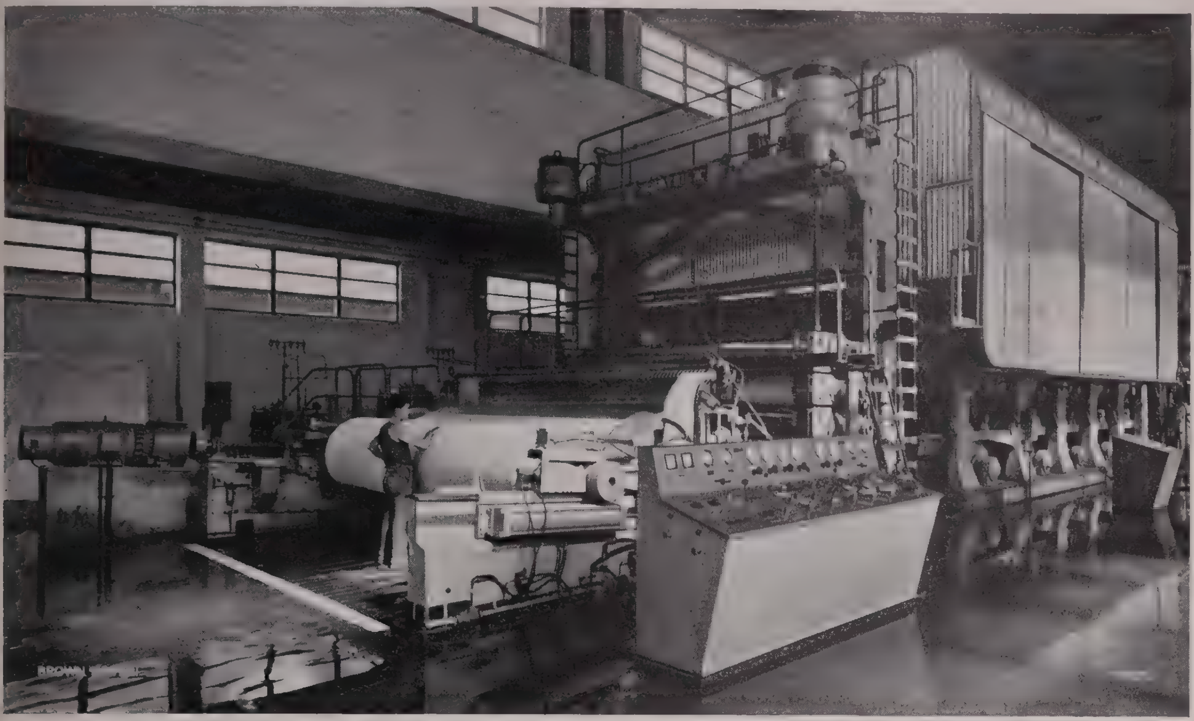


Fig. 7. – Universal-drive reel at the end of a 4500-mm paper machine with a top speed of 600 m/min

This machine produces paper with a specific weight of 40–90 g/m², with coating by the Massey process. The wind-up drum is coupled with the electrically driven transmission shaft through gearing. On the extreme left is the motor of the electro-reeler.

diameter has reached a certain size determined by the particular design, the partly wound reel of paper is swung into the horizontal position and its speed compared with that of the electro-reeler, which is already started up and running at no-load. Next the reel drive is clutched in at a speed lagging by 3–10% and the speed of the wind-up motor increased to enable it to take up the torque. Finally the reel of paper, now centre-driven, is pulled off the wind-up drum, thereby attaining the pre-selected desired tension. On reaching the visualized reel diameter, the paper is blown off and wound on to the empty reel shell which has been set up above the wind-up drum in the meantime.

Synchronization

To take over the partly wound reel from the wind-up drum to the electro-reeler, a variety of systems have been devised over the years. One worth mentioning is synchronizing with the aid of a floating contact sampling the size of the paper reel, and which automatically actuates the clutch between the reel and the electro-reeler gear. A disadvantage of this system is the troublesome adjustment of the variable contact. If it fails to

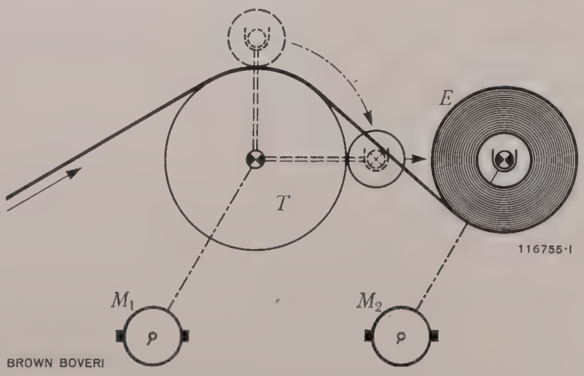


Fig. 8. – Schematic arrangement of the universal-drive reel

T = Wind-up drum
E = Electro-reeler
M_1 = Motor driving drum
M_2 = Motor driving reeler

operate, there is no alternative but to carry on winding the partly finished reel with the pope reel or to wind the paper on to a newly inserted shell.

The system employed by Brown Boveri, using a pair of tacho-generators guarantees a reliable, direct speed comparison in every position of the paper reel. The speeds of the reel and the electro-reeler are compared by means of a crossed-coil instrument calibrated in per cent. When the reeler speed is lagging by 3–10%, a contact in this instrument automatically releases a contact which throws the clutch. The over-running clutch built in the gearbox also ensures that the paper reel is taken over by the electro-reeler without any jerk.

Automatic torque take-over by the wind-up motor is made possible by a contact actuated by the clutch, which causes the speed of the drive motor to be increased accordingly. The use of stroboscopes or rotating lights is another way of achieving reliable synchronization, although the scope of the stroboscope is restricted by its unsuitability at low speeds.

The advantages of the electro-reeler and the universal-drive reel may be summarized as follows:

Simple adjustment of any desired paper tension by means of a rotary potentiometer.

Precise control of the set tension, with allowance for the losses varying with speed and diameter.

The changeover from the full reel to the empty shell by the electro-reeler is effected smoothly and without loss.

The changeover from operation by the surface-driven reel to the electro-reeler of the universal-drive reel is effected smoothly and without losses.

The paper is easily wound on the empty shell because the speed remains practically unchanged.

The entire drive is easy to operate and supervise.

By controlling to constant power, the losses experienced with the mechanically centre-driven reel are avoided.

(KME) H. PRÄKELT

VARIABLE-SPEED DRIVES IN PRINTING WORKS AND MISCELLANEOUS PAPER-PROCESSING PLANTS

676.8–83
681.62–83

In the industries dealt with in the present article the drive systems employed have become extremely varied in recent years. The most important examples are described in some detail and illustrated, not specially to recommend any particular system, but to provide an overall review in order to simplify the choice of equipment in a concrete case.

THAT these industries should be referred to collectively, rather than separately, is due the fact that the electrical equipment of the machines considered have to fulfil similar conditions regarding the basic principles and accuracy. Beyond these, of course, there are conditions peculiar to each class of machine, or which differ from one machine to another. As classes of machines we may consider the rotogravure presses, sheet-printing presses, machines producing corrugated cardboard and packing paper, coating machines, paper-sack, paper-bag and envelope machines, automatic embossing machines and folding-box glueing machines.

Compared with the paper and board mills, which are the main sources supplying the material to be printed or processed, the drive powers in these factories are, on the average, lower. For each driven unit the power required is between 1 and 100 kW. The speed range may be as much as 1:60, or even more in exceptional cases, the lower values usually only being needed temporarily. Every set speed should remain as nearly constant as possible, i.e. it must be unaffected by external conditions.

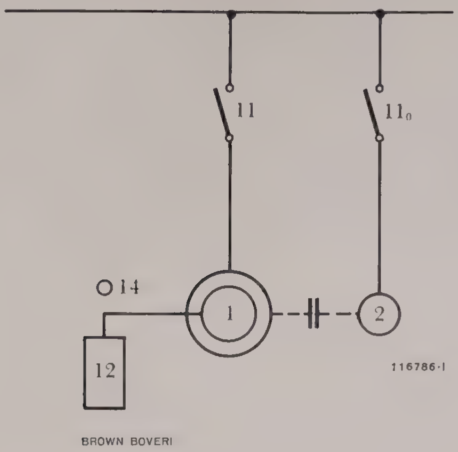
The stipulations regarding control are admittedly not so strict as, for instance, on a paper machine, and it is often possible to make do with quite simple equipment. Frequently motors having no special speed control gear may be used, on condition that their characteristic is able to assure the maintenance of almost constant speed in operation. Another kind of control system is, however, desirable or indeed essential when several motors of this kind have to drive a common shaft while running in parallel, as is often the case on rotary machines. In such cases special load-balancing devices have to be provided, to ensure that each motor bears its share of the total power and that torsional stresses in the shaft are avoided, because they can lead to disturbances in the registers.

The choice of drive systems available for the factories has grown considerably in recent years, as illustrated by the diagrams shown in Fig. 1.

In view of all these possible alternatives, which are far from exhausted, but which can be modified by variants and combinations, it is considered advisable to give some explanatory notes.

A.C. Drives

From the various diagrams in Fig. 1, the arrangement *c* stands out for sheer simplicity. The single-phase commutator motor is the sole electrical machine capable of producing infinitely variable speeds without external assistance. Greatly favoured is the three-phase shunt commutator motor, whose speed is varied simply by shifting the positions of the brushes, and which represents a combination of induction motor and frequency converter; this machine is often used for driving sheet presses (speed range 1:6) and rotary machines (up to 1:60) as shown in Fig. 2 and 3. As a result of the shunt characteristic of the motor, i.e. the small change in speed between no-load and full load, the set working speed remains practically constant without a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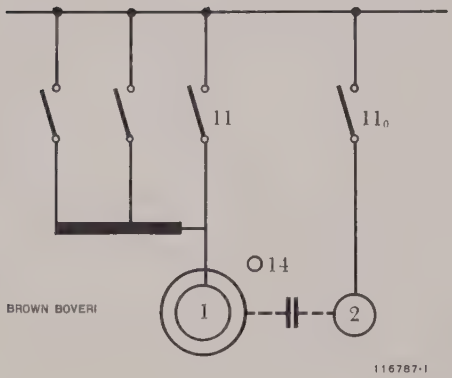
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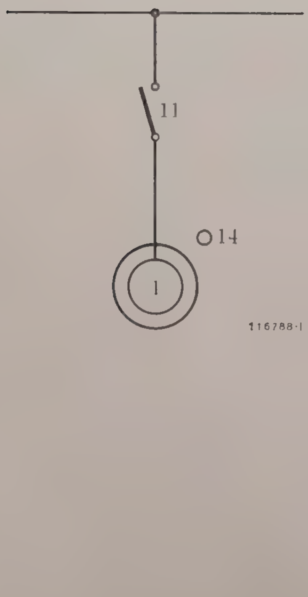
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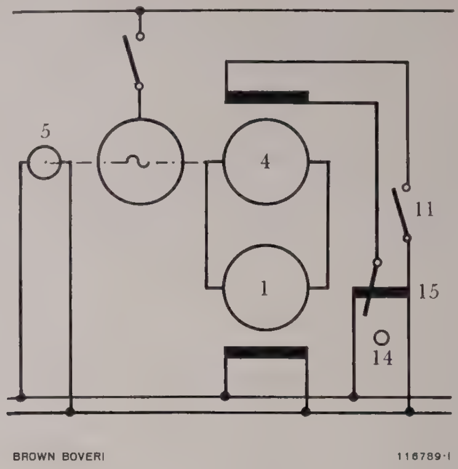
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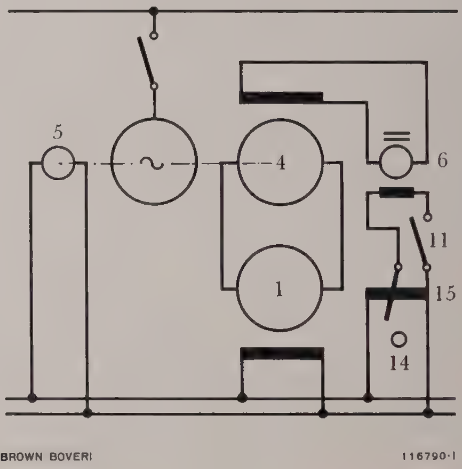
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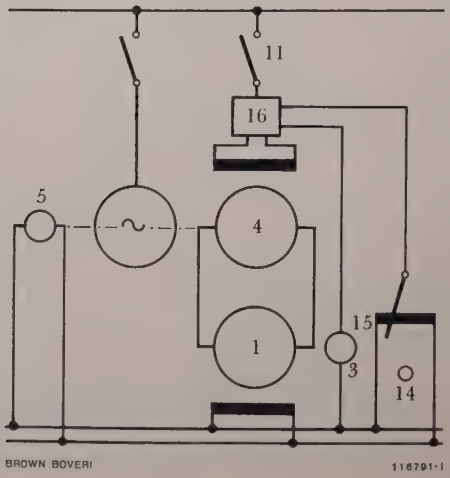
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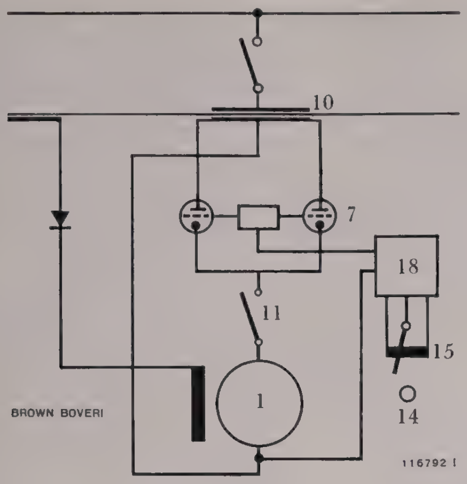

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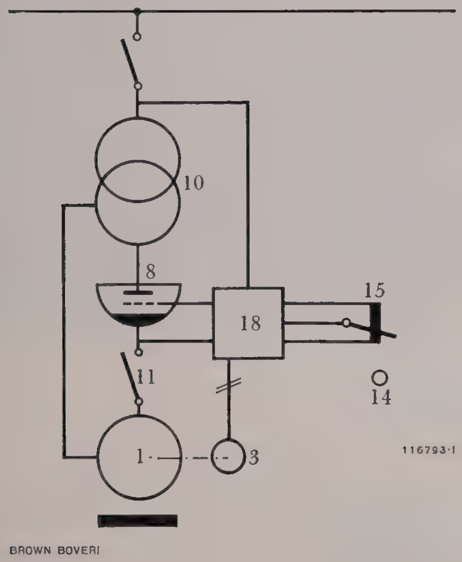

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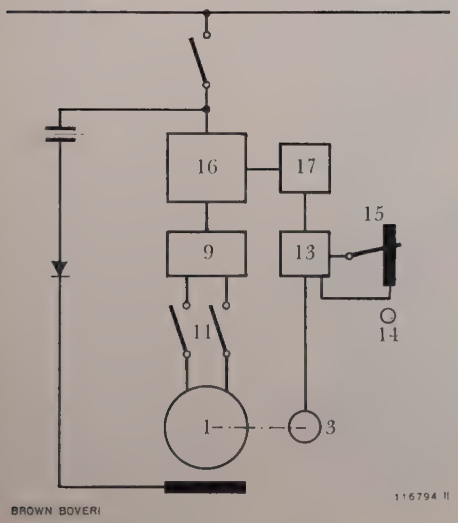

Fig. 1. – Basic circuits for variable-speed drives

a: Three-phase slip-ring motor with controller, employing an auxiliary motor for threading-in at low speed

b: Three-phase shunt commutator motor, speed variable in the working range by brush shifting, with auxiliary motor

c: Three-phase shunt commutator motor for wide speed range, controlled solely by shifting the brushes

d: Ward-Leonard d.c. motor, with converter set

e: As in d, but with an intermediate exciter for the converter set

f: Ward-Leonard d.c. motor with magnetic amplifier control

g: Tube-controlled d.c. motor (Thytron drive)

h: D.C. motor with grid-controlled mercury-arc rectifier

i: D.C. motor with semiconductor rectifier and magnetic power amplifier

1 = Motor driving the production machine
2 = Auxiliary motor for low speed
3 = Tacho-generator
4 = Ward-Leonard generator
5 = Exciter
6 = Intermediate exciter
7 = Thyratrons
8 = Mercury-arc rectifier
9 = Semiconductor rectifier
10 = Transformer
11, 11_0 = Contactor ("Inching"—or possibly for "Reverse", "Threading-in", or "Stop")
12 = Controller
13 = Regulator
14 = Remote control of brushgear motor, starter or potentiometer ("Faster"—"Slower")
15 = Potentiometer
16 = Magnetic amplifier
17 = Pre-amplifier
18 = Grid circuit

special control gear, although supervision by a regulator is feasible in principle, but is only used in special cases, such as when paper machines are driven by a single motor. The low speeds for threading-in the paper are indeed dependent on the load, but when the operating conditions were correctly estimated and the brush rocker properly adjusted on the particular machine, it was always possible to achieve perfect results, not only on normal operation, but also when setting up the machine and introducing the paper. Recently it proved possible to increase the pull-out torque by a special design of the winding, thereby greatly improving stability.

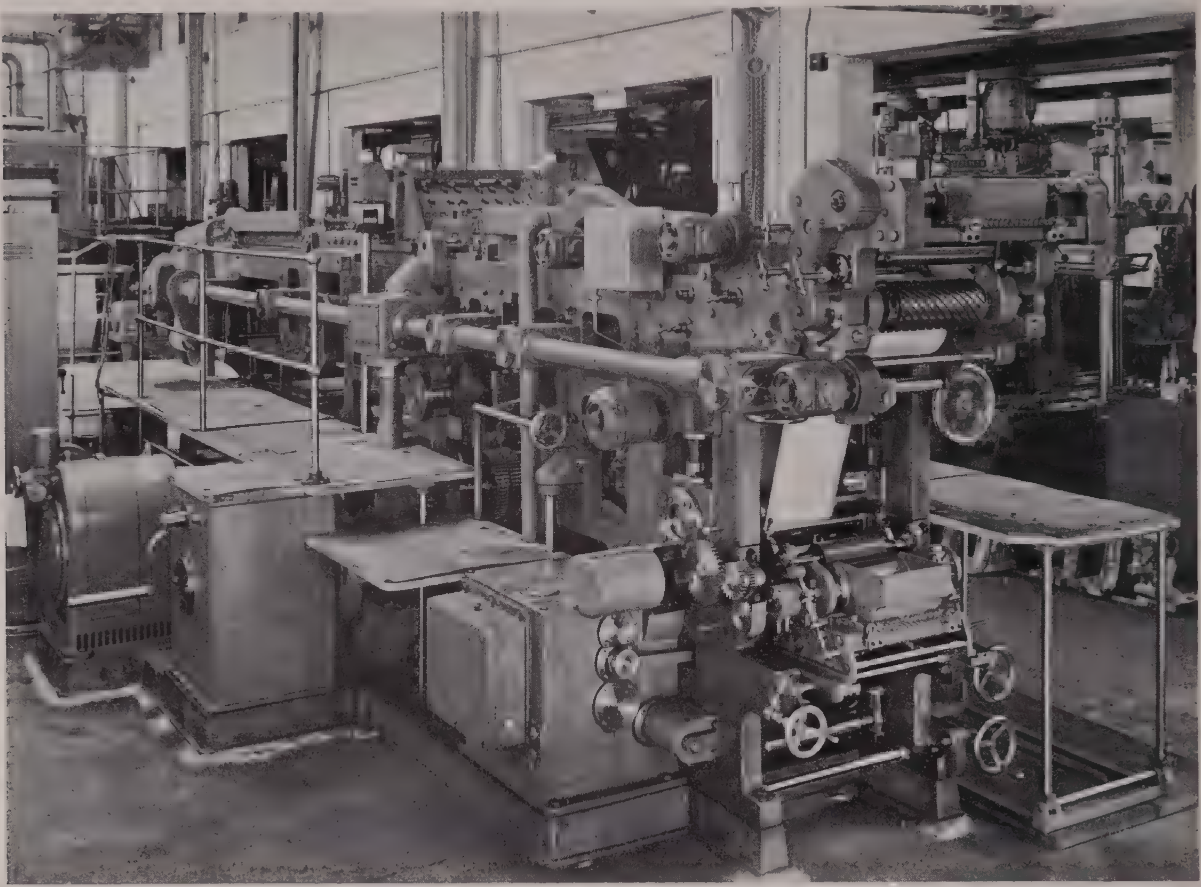

Fig. 2. – Rotary press printing postage stamps, driven by a three-phase shunt commutator motor rated 5·5 kW, 1700/170 rev/min and various smaller motors

(Winkler, Fallert & Co., Berne, Switzerland; supplied to Finlandsbank, Helsinki)
In an eight-hour day this machine prints 3 250 000 single stamps.

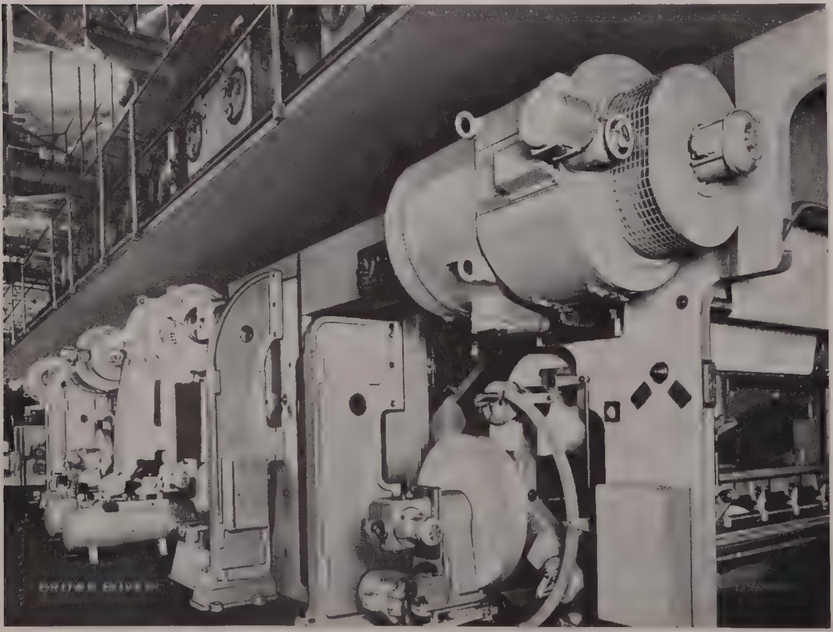

Fig. 3. – Four three-phase shunt commutator motors

42·5 kW, 1480/30 rev/min (1:50) with separately driven fans and pole-changing servomotors for brush shifting, electric braking in 5 s. Fitted to a MAN letterpress machine with 4 printing units and 2 folders, with an hourly output of 50 000 copies of a newspaper. (Supplied to Sonor S.A., Geneva, publishers of the daily "La Suisse").

Very simple too is the task of braking such motors with a wide speed range.

It is sufficient to shift the brush rocker rapidly from the operating position to the zero position, thereby causing the motor to act as a generator and return energy to the supply system, as a result of which it comes to rest in a few seconds. Plugging, in which two phases are changed at full speed, is rather a harsh method; not only does it impose severe stresses on the commutator, but also on the driven machine. Moreover, a braking resistance is required, which has to be shorted out by a contactor in normal operation, to prevent the motor from running in reverse on completion of its braking action.

Sometimes the commutator motor is only used for the actual working speed range of 1:3 to 1:6, and an auxiliary device for introducing the paper, usually an auxiliary motor with gearbox and overrunning clutch, the abrupt change from the auxiliary speed to normal working speed being damped by resistors (circuit *b*). Then the motor can be somewhat smaller, because the type is not determined by the output alone, but also by the speed range. During threading-in, the main contactor is de-energized, the auxiliary speed being independent of the load, though of course it is not adjustable. But then the larger amount of equipment for the machine and in the control board must be taken into account, and the steady change from threading-in to the working speed, which reduces the strain on the paper, must be renounced. Regenerative braking is no longer feasible because the lowest speed of the commutator motor is too high.

The speed control of the slip-ring motor, as in circuit *a*, which is effected in steps and cannot be taken much higher than about 1:3, is based on the dissipation of some of the input energy in a resistor, so that, for instance when the speed is reduced to 50% of the rated figure, there is a corresponding reduction in the output power, the rest being lost as heat. Moreover, the set speed, apart from the top speed, is severely dependent on the load. This is a simple, inexpensive drive, but one which is rather primitive and only suitable for a limited number of applications.

D.C. Drives

The development of electronics, transductors and various methods of conversion have been responsible for the increased adoption of d.c. drives in a large number of industries.

Ward-Leonard Drives of Various Forms

The classical Ward-Leonard drive is illustrated by circuit *d* in Fig. 1. In this form it is like the three-phase shunt commutator motor, i.e. it is not specially controlled and has a similar characteristic to the latter, in that it maintains the set speed constant within the working range, but at low speeds tends to depend on the load. Potentiometer 15 is used to vary the voltage of generator 4, thus setting the speed of the motor 1.

With intermediate exciter

A highly recommendable form is the circuit *e* with an intermediate exciter. The commands are imparted to this machine first, and from it to the generator, so that the control currents are naturally much lower than with direct feed. The potentiometer and contactors can therefore be a good deal smaller. Of particular value is the ability to lend the drive a definite characteristic during starting and braking. With this in mind, the exciter is equipped not with one, but with three field windings: a basic excitation winding for selection of the working speed, a counter-excitation winding for reliably adjusting the introduction speed (countering the remanence of the generator), and a compound winding influenced by the load current of the Ward-Léonard circuit. Thus a drive is obtained with very small switchgear, a wide range of adjustment, low sensitivity to changes in load and, depending on the connection of the compound winding, with adjustable smooth start or with abrupt start. An

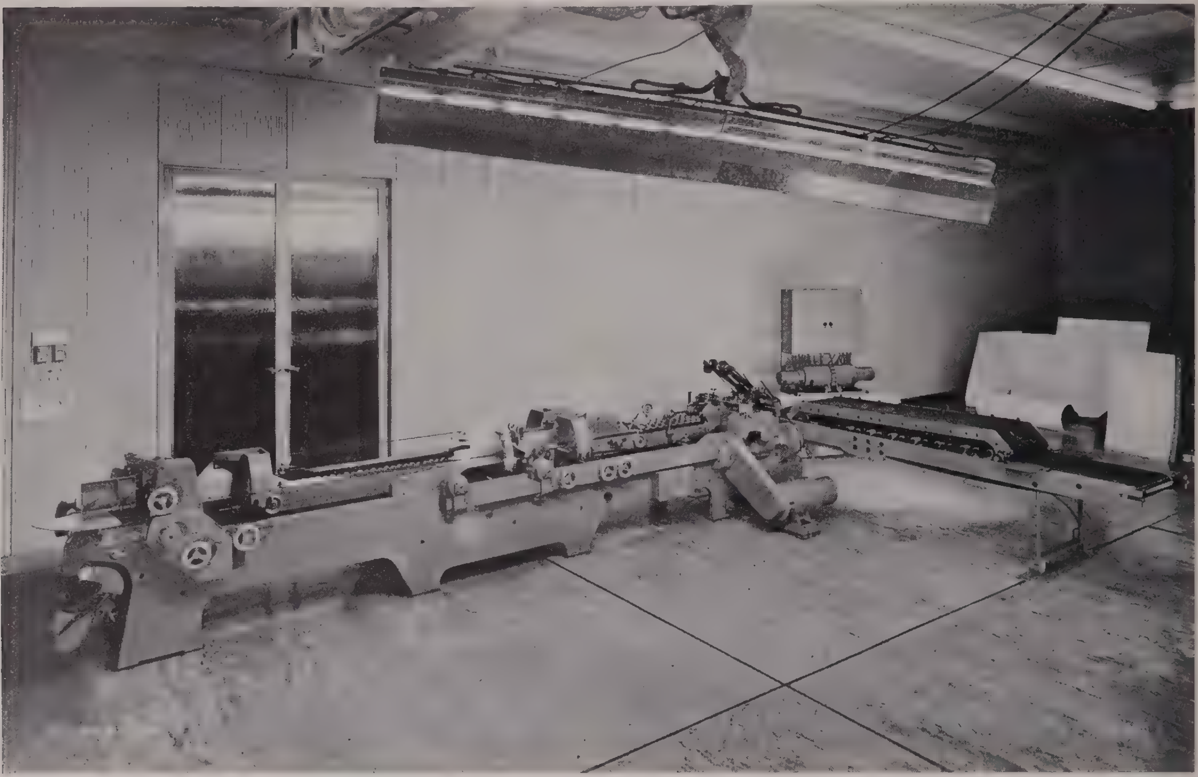

Fig. 4. – Bobst box-folding and glueing machine, driven by a 6-kW d.c. motor, 2300/38 rev/min (1:60); Ward-Leonard control with intermediate exciter

Electric braking in 1·5 s. On the right, above the rotating converter, is the control gear cabinet. This machine turns out up to 90 000 cardboard boxes an hour.

example of an installation in which this drive is used can be seen in Fig. 4 (the drive of a folding-box glueing machine).

With magnetic amplifier

In circuit *f* the intermediate exciter is replaced by a magnetic amplifier fed from the mains, which as a variable inductive resistance acts through dry-cell rectifiers on the field of the generator, but which can also be used as a voltage or speed regulator. In it the voltage of the tacho-generator 3 is compared with the voltage picked off the potentiometer 15, providing the actual value. In contrast to the preceding circuits, this is a drive with pronounced speed control. When several motors in parallel have to drive a common shaft, the same magnetic amplifiers can quite easily be utilized for balancing the load. Very good results have been obtained with this system both on letterpress and rotogravure machines, each section of which is equipped with a separate Ward-Leonard unit comprising d.c. machine and squirrel-cage motor (known as a multi-generator sectional drive). This is the circuit used for the double drive of the coating machine illustrated in Fig. 5.

Thus with all these variants the d.c. drive motor is connected to the mains through a rotating converter. The latter simultaneously acts as control element for adjustment of the Ward-Leonard voltage, i.e. for the speed of the motor, and thus corresponds in this respect to the internal speed adjustment of the commutator motor (control winding, commutator and brushes). This explains why the d.c. motor is bound to be smaller and lighter than the commutator motor with the same rating and the same speed range, which of course contains

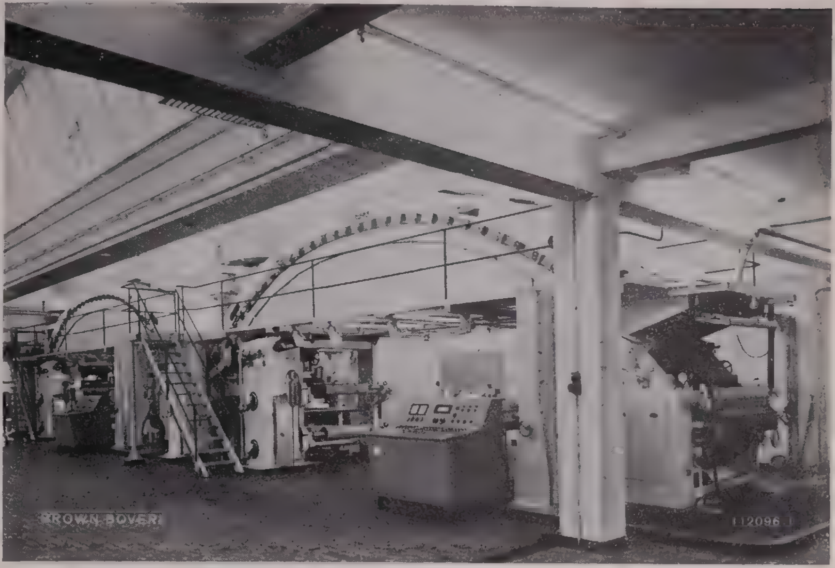

Fig. 5. – Jagenberg coating machines driven by two d.c. motors rated 15 kW, 1500/75 rev/min (1: 20)

The two coating machines can work separately or together. The motors are controlled by the Ward-Leonard system with magnetic amplifiers, which maintain constant speed and balance the load in parellel operation. The rotating converters with the switchgear are in the cellar. (Installed at: Rationelle Verpackung AG., Affoltern, Zurich, Switzerland.)

the converter—in the latter case a frequency converter—in itself. The d.c. system occupies less space by the machine, but instead needs extra space and cooling for the control set some distance from the actual machine, although this set can be supplied as a vertical monobloc, if desired. The motor driving the converter, as mentioned already, is a squirrel-cage motor started by a manually or remote-controlled star-delta switch.

Like the three-phase shunt commutator motor, the Ward-Leonard drive affords the welcome opportunity of being able to brake regeneratively at little expense. If the excitation is removed when the "Stop" command is given, the voltage at the d.c. motor dominates and it is driven as a generator, feeding back into the converter so that it runs above its synchronous speed and returns the braking energy to the mains. A special winding in the generator, which is switched in at reduced voltage just before the end of the braking process, ensures that the machine stops precisely.

Rectifier Circuits

In the last three variants illustrated in Fig. 1, the task of the rotating converters is taken over by rectifiers; in circuit *g* thyratrons are used, in circuit *h* mercury-arc rectifiers, and in *i* semiconductor rectifiers.

Thytron drives

The drive employing thyratrons, which are gas or vapour-filled electron tubes, can only be economically designed for low-powered drives. Fig. 6

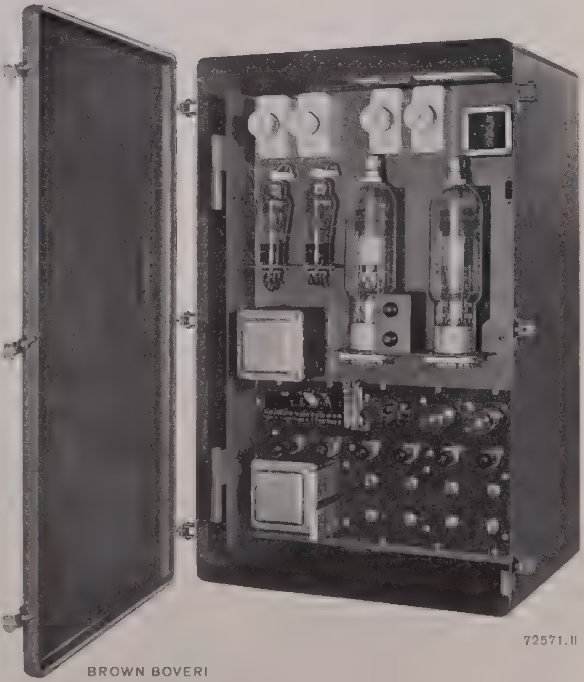

Fig. 6. – Cabinet containing the apparatus for the Thytron drive of an offset press

The two large tubes on the right are the thyratrons feeding the armature; the smaller ones on the left are high-vacuum tubes for the field and the control system.

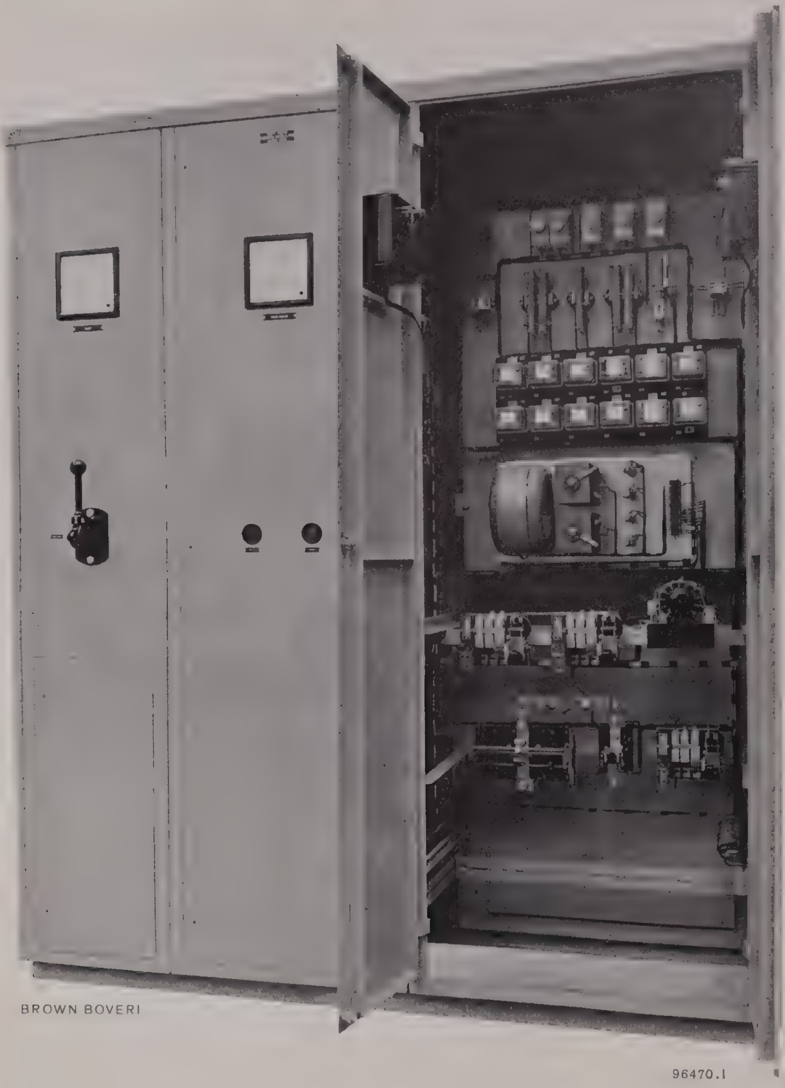

Fig. 7. – Switchgear cabinet

for the drive of a letterpress machine made by Winkler, Fallert & Co., Berne, driven by d.c. motor with magnetic amplifier, seen in the middle of the right-hand open section. On the right below it is the remote controlled potentiometer for adjustment of the speed. (Installed at the Courvoisier printing works, La Chaux-de-Fonds, Switzerland.)

shows the case containing the apparatus for the Thytron drive of a small offset machine.

In connection with the question of space it should be pointed out that for the conversion a power transformer is required, from which the a.c. power flows to the valves. The speed is automatically controlled, in that the armature voltage—as actual value—or if greater accuracy is required, the output voltage of a tacho-generator, is compared with the reference value set on a potentiometer.

Regenerative braking is not readily feasible with this kind of drive. It is therefore necessary to resort to a braking resistor, in other words the Ward-Leonard circuit is opened and the motor made to run out through a resistor, in which the energy is dissipated. This circuit produces sharp braking to begin with, but the effect dies away towards the end and can only be effective right down to standstill if an increased number of steps with corresponding contactors are used.

For higher powers this circuit can be combined with a Ward-Leonard circuit, in which case only the control tasks are performed electronically.

Mercury-arc rectifiers

Drives employing mercury-arc rectifiers, as shown in circuit *h* of Fig. 1, have already been used for rotary machines. In general, though, it should be remembered that their advantages only take real effect at high voltages and currents. In the field under discussion they will in all probability have to give way to the drives described below.

Semiconductor rectifiers

Recently drives have been devised employing semiconductor rectifiers, with the circuit shown at *i* in Fig. 1. These units employ extremely pure crystals, particularly of silicon, which possess a strong blocking effect in one direction, but allow a certain current to pass in the opposite direction. They are enclosed in a copper capsule of small dimensions, forming the one pole, while the other pole is brought out by a flexible lead. Depending on the magnitude of the load current, a number of these cells are connected in parallel, mounted in a framework and housed in a cabinet.

Admittedly these new elements cannot be controlled at the present stage of development, that is to say, the conversion from a.c. to d.c. is fixed. Variable-speed d.c. drives, however, require a variable voltage. Hence additional induction regulators or magnetic amplifiers must be installed for the full power throughout. The speed is controlled with the aid of a tacho-generator, while resistors are again used for braking. The drive using semiconductor rectifiers is at present being developed.

Switchgear, Operation and Maintenance

The switchgear and installation work are simplest with the a.c. drives. On the other hand it is noteworthy that in the circuits *d*, *e* and *f* in Fig. 1, the Ward-Leonard circuits in which the load current flows are quite closed and contain no contactors, but merely protective relays. The entire process of control is thus delegated to the auxiliary circuits, in which only light currents have to be handled.

Fig. 7 shows the switchgear cabinet of a Ward-Leonard drive with magnetic amplifiers. In the background of Fig. 8 a similar cabinet can be seen

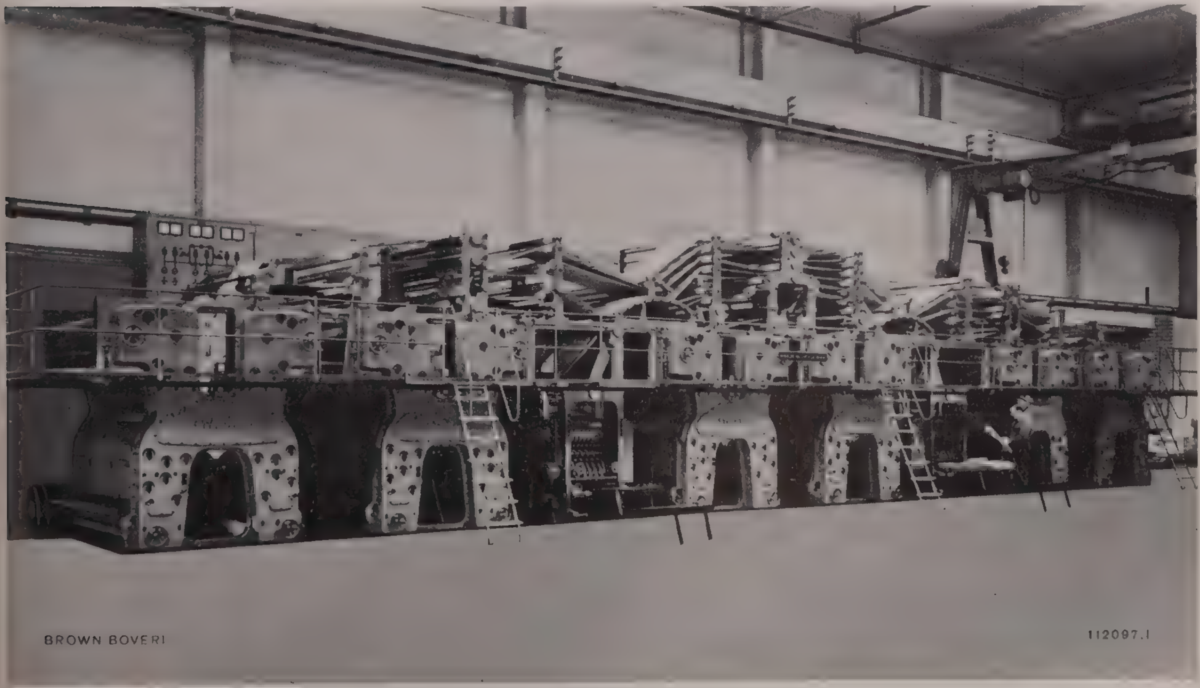

Fig. 8. – Operating side of a letterpress machine with six printing units and two folders, driven by six three-phase shunt commutator motors rated 47 kW, 1500/214 rev/min, with auxiliary motors for threading-in the paper

One of the main motors can be seen on the left. Behind it is the switchgear with coupling panel and mimic diagram. (Installed at: Imprimerie Industrielle, Issy-les-Moulineaux, France.)

belonging to an a.c. drive (in both cases for a rotary letterpress machine).

The operation of the driven machine is independent of the drive system. Commands are always imparted by push-buttons, rotary switches, signalling or safety devices, to the control gear, regardless of the nature of the latter, and so to the motors as executive elements. In the case of Thytron drives the cathodes have to be heated before the drive can be taken into service each time, necessitating a wait of about 3 minutes.

In this chapter a further special device will be referred to, namely the system of preselecting the speed, or automatic repetition of the speed. By this it meant that the machine, after being switched off for a short time, automatically runs up again to the previously set working speed. For this, either a mechanism with moving auxiliary contacts on the speed adjustment can be used, or an electrical system of follow-up control.

As regards maintenance these different drive systems are all fairly similar. At the most it may be said that in the event of faults in the traditional control systems, the electrician can easily find out the trouble, whereas special training is necessary for the various kinds of drives employing rectifiers.

Efficiency and Power Factor

The question of efficiency and power factor of these drives is sure to arise. If an efficiency of 80 % is chosen as a basis for comparison, corresponding roughly to a fairly large three-phase commutator motor with a wide speed range, running at top speed and full torque, the corresponding Ward-Leonard drives can be expected to attain about 73–75%, allowing for converter losses, and 83–85% with rectifier drives. At 3/4 of full speed these efficiencies are 80%, 72–74% and 77–79%, respectively, from which it is evident that they vary in service, in favour of the one system or the other. The relevant power factors at full speed are 0·97 leading, 0·85 lagging and 0·89 lagging, respectively, dropping to 0·89 lagging, 0·8 lagging and 0·8 lagging respectively, at 3/4 full speed. All these figures are approximate and are only intended to give a rough comparison.

Conclusions

Reviewing the drive systems dealt with in the present article, it is clear that each has its own advantages and disadvantages, and that there is no single system combining all the advantages. Moreover it is evident that, for a definite drive power, it is always necessary to invest a certain amount in equipment, although the distribution of the latter can be different from one case to another.

A final factor which is most important is the reliability of the installations mentioned at the beginning of the article, especially in works printing newspapers. This fact is taken fully into account when the electrical equipment is being planned and constructed, regardless of which kind it may be.

(KME) P. WOLFENSBERGER

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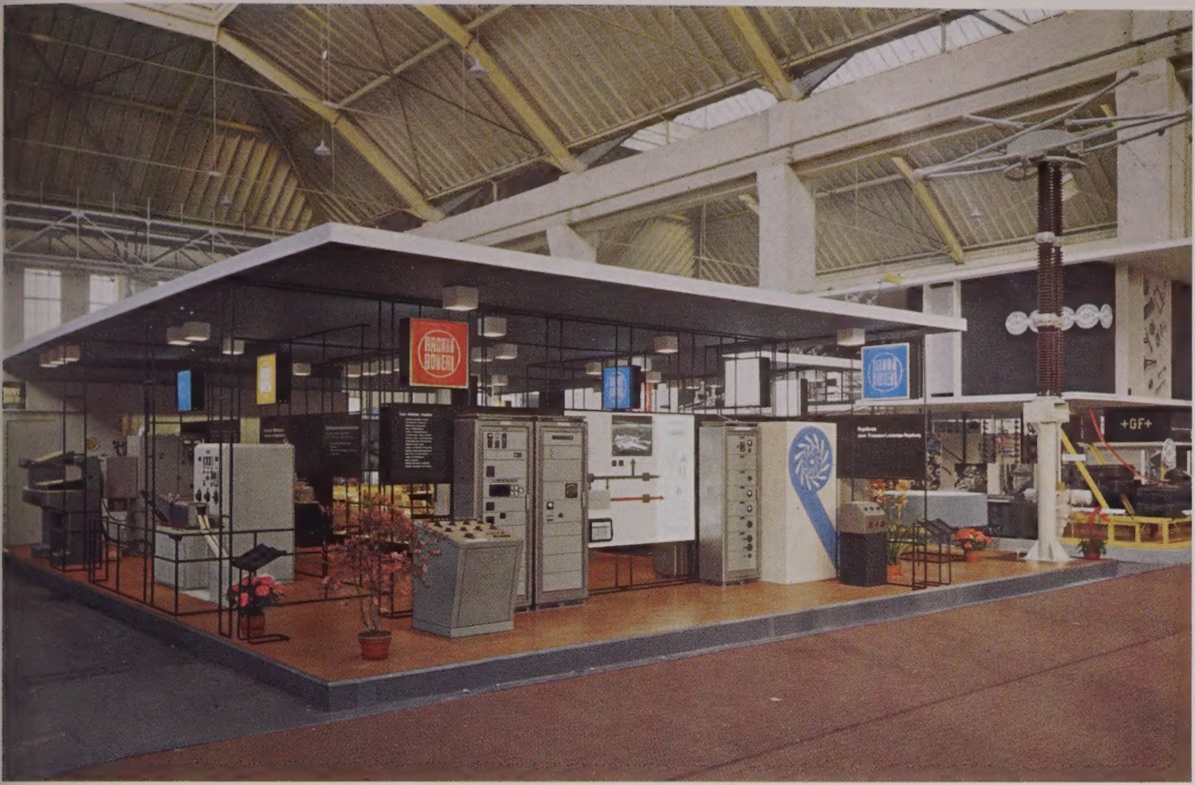

Brown Boveri at the Swiss Industries Fair 1960 in Basle

Above: The main stand with (extreme right) one pole of a single-column isolator for 420 kV, digital system controller for power stations, high-speed distance relay, on-load isolator, silicon rectifier, standardized motors, twinstop motors, medium-frequency induction plant for forging and heat treatment, radio-frequency generator, electron tubes, exhaust-gas turbocharger.

Below: The joint Brown Boveri-Arcos stand for electric welding.

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